ISOSTASY

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BY

WILLIAM BOWIE

CHIEF, DIVISION OF GEODESY, U. S. COAST AND GEODETIC SURVEY

PRESIDENT, SECTION OF GEODESY, INTERNATIONAL GEODETIC AND GEOPHYSICAL UNION

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PREFACE

THE time seems to have arrived when there should be made more readily available the results of the investigations leading to the proof of the isostatic condition of the earth's crust, and the results of the attempts to apply the isostatic principle to some of the major geologic problems.

Reports and papers have appeared from time to time as the investigations progressed, but one must consult many of them to be able to form a clear picture of what has been accomplished. The writer has attempted to present in this work in a brief form what he thinks are the essential data and results. The original data and their analyses are so voluminous that the reports containing them must be consulted by those who may wish to consider the subject in an exhaustive way.

The writer has considered with care the two views on isostasy, one holding that the earth's crust extends to a certain depth below sea level, with varying densities of crustal material under elevations and depressions, and the other that the crustal matter has uniform density with varying thicknesses. The former is generally

spoken of as the Pratt theory and the latter the Airy theory. The writer is convinced from his studies that the former is a logical one, and that the latter is untenable. In applying isostasy to the consideration of the earth's crust and the processes which cause horizontal and vertical movements of the surface, the writer uses the Pratt theory.

The mass of geodetic, geophysical, and geological literature dealing with isostasy is enormous. While a number of references to reports, books and papers have been given, the reader must consult the Bibliography of Isostasy, prepared by Prof. Adolph Knopf, of Yale University, and published in 1924, by the National Research Council, Washington, D. C., for the most complete list existing.

The first comprehensive investigations were made by the late John F. Hayford, when he was in charge of the geodetic work of the U. S. Coast and Geodetic Survey. Since 1909 the investigations of that organization of the subject have been conducted by the writer. Many geodesists of other countries have also made studies. Included among them are:

F. R. Helmert, S. G. Burrard, E. O. Schiøtz, T. Niethammer, A. H. Miller, Otto Klotz, O. Hecker, G. Perrier, G. Sans Huélin, W. Heiskanen, W. de Sitter, and H. L. Crosthwaite.

The attempts in this book to interpret geo-

logic processes in the light of isostasy may result in stimulating investigations and analyses which should go far towards substantiating ideas presented or proving them not to be valid. The writer wishes to acknowledge the help he has received from reading the works of others who have presented their views on the relation of isostasy to geology. There are many authors in this category, but the outstanding ones are:

C. E. Dutton, Joseph Barrell, H. F. Reid, G. K. Gilbert, A. C. Lawson, F. Nansen, S. G. Burrard, C. K. Leith, R. A. Daly, and W. M. Davis.

The writer wishes to pay tribute to the two Directors of the U. S. Coast and Geodetic Survey, O. H. Tittmann and E. Lester Jones, whose support and encouragement made possible the isostatic investigations carried on by Hayford and the writer. But even with their help the results accomplished were only possible because of the able assistance of the members of the Geodetic Division of the Survey. Especial mention must be made of C. H. Swick, W. D. Lambert, H. C. Mitchell, and the late Sarah Beall. The present Assistant Director of the Survey, R. L. Faris, has been unsparing in giving his time to discussions with the writer on the many ramifications of the isostatic investigations. His support and sympathetic attitude have been of the greatest value.

Most of the illustrations in this book have been used by the author in a number of his reports and papers; they are furnished for use in this volume by the U. S. Coast and Geodetic Survey, with the permission of the Director of that bureau, E. Lester Jones. In all other cases, specific credit is given.

CONTENTS

LIST OF ILLUSTRATIONS

I S O S T A S Y

ISOSTASY

CHAPTER I

DEVELOPMENT OF THE ISOSTATIC THEORY

First Isostatic Ideas

Isostasy is a condition of the outer portion of the earth, called the crust, proved to exist by means of geodetic data. These data are usually employed in the determination of the shape and size of the earth. The word isostasy is derived from Greek words and it may be defined as "equal standing" or "equal pressure." The isostatic investigations have shown that a level surface about 60 miles below sea-level is also a surface on which the outer material of the earth exerts a uniform pressure.

We are forced to the conclusion, as a result of the proof of isostasy, that the average densities of the earth's materials above the 60-mile surface vary from place to place. We may assume that the average density for the 60-miles under the coastal plains is normal. Under the conti-

nents and the larger islands, the average density is less than normal, while the average density of earth material under oceans is greater than normal.

The proof of isostasy is having a profound effect on geological and geophysical thought. The isostatic condition of the outer portion of the earth must be given careful consideration and full weight in hypotheses and theories advanced to account for the great changes that have taken place in the earth's surface during geological times.

It is hoped that some geologist versed in the early geologic literature will tell us some time of the first glimmerings of the isostatic idea. This would make an interesting and valuable historic document. It is well known that Babbage and Herschel in the early part of the last century helped to lay the foundation on which the isostatic superstructure was begun by Airy and Pratt and completed by Dutton and those who came after him.

Geologists and geodesists share the credit of the proof of isostasy. Without geologic knowledge the geodesists could not have properly interpreted the geodetic data and could not have planned the campaigns of investigations which have changed isostasy from a theory to a scientific principle.

As is well known, the dimensions of the earth

are determined by comparing the measured and computed distances between places at which the astronomic latitudes have been observed. If the earth were a true sphere with a perfectly smooth surface and the densities of the earth material varied in the same way along all the radii of the earth, if two astronomic latitudes in a north and south line could be determined without error, and if the distance between the two latitude stations could be measured with absolute accuracy, the exact circumference and diameter of the earth could be computed. (See Fig. 1.)

Suppose the conditions of the earth to be the same as above with the exception that the surface is a spheroid instead of a sphere, a meridional section being an ellipse instead of a circle. In this case it would be necessary to have three latitude stations with measured distances between them, or two pairs of stations in different latitudes with the distance measured between the stations of each pair. With these data the major and minor axes of the ellipse could be computed, and the shape and size of the earth become known. (See Fig. 2.)

But the earth's surface is not a mathematical figure and the variation of densities along the earth's radii may or may not be the same. Therefore, in the early determinations of the shape and size of the earth many astronomic stations were used on the assumption that the effect of

the surface irregularities would be balanced. This assumption worked quite well when the geodetic data were for comparatively flat areas

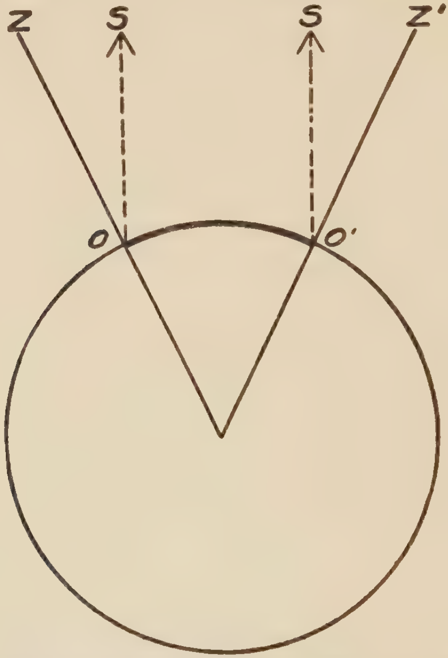


FIG. 1.—If the earth were a true sphere the linear value of one degree of latitude could be obtained by measuring the distance from O to O', two stations on the same meridian, and by the measurement of the angle at O between the zenith Z and the star S and the angle at O' between the zenith Z' and the star S. The star at the time of observation must be on the meridian. Since the distance from the earth to any star is very great, directions to it from different places on the earth may be considered as parallel. With the linear and angular distances between the stations, the dimensions of the earth can be readily computed.

such as in certain parts of Europe. It was from data in those areas that the earliest determinations of the dimensions of the earth were derived. But later on, attempts were made to use

the data collected in India. To the south there were broad and rather level areas with a great mountain system to the north. Here the con-

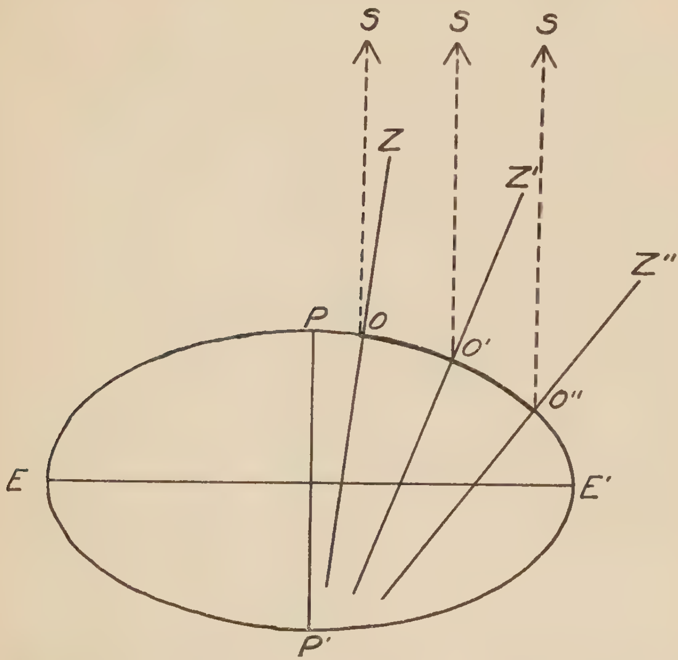


FIG. 2.—If the surface of the earth were a true spheroid whose meridional section would be an ellipse the dimensions of the earth would be obtained by comparing the linear and angular distances between three points on a meridian, O, O' and O''. The earth's surface is not a true spheroid and, therefore, many stations at which astronomic observations are made must be connected by linear measurements to furnish the data necessary to determine the shape and size of the earth.

ditions were far different from those in Europe. The theory of isostasy would have come eventually, but the configuration of India was just what was needed to give it birth.

Deflections of the Vertical in India

Airy and Pratt in using the India data in their figure of the earth investigations found large differences in the lengths of degrees of latitude as measured by triangulation between latitude stations near and far from the Himalayan Mountains. The normal change in the length of degrees of latitude from the equator towards the poles is small. For successive degrees the maximum difference in length is 0.013 mile. In India far greater differences than this were found and there was no regularity in them.

Airy and Pratt made computations of the effect of the Himalayan Mountains on the direction of the plumb line, to which all astronomic observations are referred. Before their time mountain masses were considered to be loads held in position because of great strength of the earth. When the effects of the mountains were applied as corrections to the astronomic latitudes, it was found that they were far too great to bring into agreement the latitudes derived from astronomic observations and from triangulation. The length of a degree of latitude equivalent to a distance of about 69 miles can be measured by triangulation with an error of less than 3 meters (10 feet).

We have to rely upon written records to learn how Airy and Pratt developed the idea that the mountains were underlaid by abnormally light

material. Probably there had been much discussion among the investigators and their associates before they put their thoughts into print. Most new scientific hypotheses and theories are preceded by periods of time of varying length before their definite formulation, and it was no doubt so with isostasy.

The first clear-cut ideas published on the floating crust are contained in five papers, one by Airy and the others by Pratt, all published in the *Philosophical Transactions* of the Royal Society of London.[1]

We find little of note on the floating theories of the earth's crust after Airy and Pratt until 1889, the year of Dutton's address. The papers which did consider the subject were written largely by mathematicians, physicists, and geodesists. From 1889 there has been a great growth in the floating crust (isostasy) literature, and geologists have contributed their share.

Although the discovery that the earth's crust is floating resulted from the use of deflections of

[1] G. B. Airy; On the computation of the effect of the attraction of mountain masses as disturbing the apparent astronomical latitude of stations in geodetic surveys. Vol. 145, page 101, 1855.

J. H. Pratt; On the attraction of the Himalayan Mts., and of the elevated regions beyond upon the plumb line in India. Vol. 145, page 53, 1855. On the influence of the ocean on the plumb line in India. Vol. 149, page 779, 1859. On the deflection of the plumb line in India caused by the attraction of the Himalayan Mts., and of the elevated regions beyond; and its modification by the compensation effect of a deficiency of matter below the mountain mass. Vol. 149, page 745, 1859. On the constitution of the solid crust of the earth. Vol. 161, page 335, 1871.

the vertical, and the same kind of data were used in Hayford's first test of the theory of isostasy, the intensity of the earth's pull on an object at its surface, called gravity, is equally effective in testing the theory of isostasy.

With gravity data the shape of the earth may be determined, but not its size; only by means of astronomic determinations of latitude and longitude and the measurement of distances between astronomic stations by triangulation or otherwise, may data be obtained for the determination of the size of the earth.

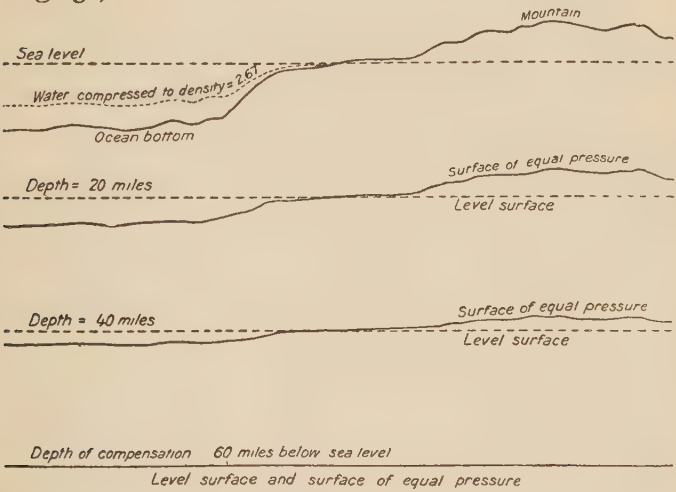
Isostasy According to Airy

Airy's conception was that the continents and islands are resting hydrostatically on highly plastic or liquid material, with roots or projections extending into the inner material, just as icebergs project downward into water. The greater the elevation of the continent or island the deeper is the downward projection. The greater elevations were due, according to Airy's views, to greater thickness of crustal material beneath.

Isostasy According to Pratt

Pratt's views were that the continents and islands project above the average elevation of the solid surface of the earth because of material of less density beneath them; the higher the sur-

face the smaller the density. He held that the crustal matter extends to a uniform depth below sea level, where the earth's materials change from a solid to a yielding condition. (See Fig. 3.)



PRATT ISOSTASY

FIG. 3.—According to the Pratt isostasy, level surfaces 60 miles or more below sea level are also surfaces of equal or uniform pressure. Above the 60-mile depth, surfaces of equal pressure have the general shape of the outer surface of the earth and they are not level. At all depths above the 60-mile surface there are stresses exerted in a direction from the high areas toward the low ones.

The fundamental difference between Airy's and Pratt's views is that the former postulated a uniform density with varying thickness, and the latter a uniform depth with varying density.

Dutton's conception of isostasy was that of

Pratt. The Pratt theory is more in vogue than that of Airy, though the latter has some strong advocates,—among whom are: Osmond Fisher, Alfred Wegener, A. Born, and A. C. Lawson.

The isostatic investigations conducted by the U. S. Coast and Geodetic Survey under the direction of the late J. F. Hayford and the writer, which proved the theory of isostasy, are based on the Pratt conception. Those investigations were the first brought to a definite conclusion. In them were used vast quantities of geodetic data most of which related to the United States. Mention must also be made of the masterful research by Sidney Burrard while Superintendent of the Trigometrical Survey of India. The results of his investigations supplemented and strengthened the conclusions of Hayford and the writer, and the reports and papers issued by the three should be considered jointly by the student who may wish to resort to original sources. These investigations were quantitative and in them accurate values of gravity at many stations, and numerous deflections of the vertical were used.

G. R. Putnam in the last decade of the 19th century, when a member of the U. S. Coast and Geodetic Survey, really made the first quantitative test of the theory of isostasy, but his conclusions were very general in character.

The qualitative side of the theory of isostasy

has been extensively considered by many students of the earth; their number is great and their names, therefore, cannot be given here. Some of the earlier ones, with titles of their works, are given on pages 135 to 138 of *Special Publication No. 40* of the U. S. Coast and Geodetic Survey, which was printed in 1917. For a more complete and recent list of writers see "Bibliography of Isostasy" by Adolph Knopf, printed by the National Research Council, Washington, D.C., in 1924.

The merits of the two conceptions of isostasy by Airy and Pratt are set forth elsewhere in this book.

Dutton on Isostasy

On April 17th, 1871, C. E. Dutton read a paper entitled "The Causes of Regional Elevations and Subsidence," before the American Philosophical Society, a summary of which appeared on pages 70 and 72 of the *Proceedings* of that society, Vol. 12, 1871–72. He remarked upon his desire to submit certain of his views regarding the causes of regional uplift and subsidence. He stated that he was unacquainted with any views on this subject in the writings of geologists which seemed to him satisfactory. This would lead one to believe that Dutton had rather carefully scanned the geological literature, prior to the presentation of his paper, for

the purpose of learning the views of geologists on the major changes in elevation of the earth's surface.

Dutton outlined in his paper the theory that changes in density were the primary cause of the surface elevation. He felt that metamorphism, which in his judgment extended down through the sedimentary rocks, was the primary cause of the increase or decrease in the density of rocks. He concluded that if there were a 5 percent change in density as a result of metamorphism the average elevation of the North American continent above the ocean could be accounted for by the expansion of a series of rocks as thick as the carboniferous in the State of Pennsylvania. He held that the metamorphic action probably extended to a depth of at least eight or ten miles.

Dutton thought that rocks far down below the surface, aided no doubt by heat under the influence of great pressure, take up large quantities of water, carbonic acid, and sulphuric acid, become softened and assume a density lighter than the average mass of overlying rock. In a somewhat similar manner Dutton explained the intrusion of traps, trachytes, and basalts.

The summary of Dutton's paper closes with the following statement:

> If the views be correct, then we ought to expect that volcanic regions will be confined to those areas which

> have recently been regions of marked elevation. And we find this to be the case. In America, the whole extent of the Rocky Mountains and of the Andes, so far as known, was covered by the ocean at the beginning of the Tertiary period. The elevation of the Rocky Mountains was probably earlier than that of the Andes, and sooner completed. Hence, while the former was the scene of an unparalleled amount of volcanic action during the Pliocene and Miocene, and is now nearly, or quite, quiescent, except in Southern Mexico, the Andes still abound in active volcanoes. The East Indian volcanic regions are all of Tertiary formation, as are those of the Mediterranean and the Auvergne.

Seventeen years later Dutton had arrived at the definite conclusion that the major changes in elevation of the earth's surface could not be caused by collapse of the crust on a shrinking nucleus, called for by the contractional hypothesis. He believed the fundamental cause of the vertical and horizontal surface changes is erosion and sedimentation, and he considered the crust to be weak enough to yield under the unloading and loading. His views on this subject are given in his paper entitled, "On Some of the Greater Problems of Physical Geology" delivered before the Philosophical Society of Washington on April 27th, 1889, and printed in *Bulletin No. II* of that society. The paper was re-printed in the Sept. 19, 1925, number of the *Journal* of the Washington Academy of Sciences. Some of the views expressed in that paper are summarized below.

He stated that the forces which act on the earth's mass are gravitation and the forces resulting from the rotation of the earth on its axis. He stated that the earth, if composed of homogeneous material, would assume the form of an oblate spheroid, but if heterogeneous, with some parts heavier or lighter than others, the normal figure would not be spheroidal. In this connection he said:

> Where the lighter matter was accumulated there would be a tendency to bulge, and where the denser matter existed there would be a tendency to flatten or depress the surface. For this condition of equilibrium of figure, to which gravitation tends to reduce a planetary body, irrespective of whether it be homogeneous or not, I propose the name Isostasy. I would have preferred the word isobary, but it is preoccupied. We may also use the corresponding adjective, isostatic. An isostatic earth, composed of homogeneous matter and without rotation, would be truly spherical. If slowly rotating, it would be a spheroid of two axes. If rotating rapidly within a certain limit, it might be a spheroid of three axes.
>
> But if the earth is not homogeneous—if some portions near the surface are lighter than others—then the isostatic figure is no longer a sphere or spheroid of revolution, but a deformed figure bulged where the matter is light and depressed where it is heavy.

In the above quotation from Dutton's paper the word *isostasy* made its first appearance.

After presenting evidence to show that the earth's crust sank under the weight of sediments,

and was uplifted to restore equilibrium under areas of erosion, he gave an idea of the mass which may not escape isostatic equilibrium:

> The magnitudes of the masses which thus show isostatic tendency are in some cases no greater than a single mountain platform, less than a 100 miles in length, from 20 to 40 miles wide, and from 2500 to 3500 feet mean altitude above the surrounding lowlands. From this we may directly infer that in those regions the effective rigidity of the earth is insufficient to uphold a mass so great as one of those platforms if that mass continued a real deformation of isostasy; and if an equal mass were to be suddenly removed the earth would flow upward from below to fill the hiatus; hence we must look to considerably smaller masses to find a defect of isostasy. It is extremely probable that small or narrow ridges are not isostatic with respect to the country round about them. Some volcanic mountains may be expected to be non-isostatic, especially isolated volcanic piles.

The magnitude of the mass which is compensated, according to Dutton, is of the order of magnitude of the mass proved to be at least largely compensated by the isostatic investigations made by the writer. See page 104.

Dutton next stated that values of gravity and deflections of the vertical substantiate the views advanced by him. He claimed that the weight of the sedimentary material derived from the land and deposited along the coastal waters constitute a static force acting on a viscous support below which would tend to push the loaded sea

bottoms horizontally inward upon the unloaded land.

> This gives us a force of the precise kind that is wanted to explain the origin of systematic plications. Long reflection and considerable analysis have satisfied me that it is sufficient both in intensity and in amount unless we assume for the mean viscosity of the superficial and subterranean masses involved in the movement a much greater value than I am disposed to concede. The result is a true viscous flow of the loaded littoral inward upon the unloaded continent.

It must be true, since isostasy exists, that there is a movement from the area of sedimentation toward that of erosion, but while Dutton claimed the movement is of "loaded littoral," the isostasists of today hold that the movement occurs in sub-crustal space, and not near the surface.

Dutton held that the parallelism of the folds in a mountain system, and their occurrence in long narrow belts are caused by the horizontal forces developed by the weight of the sediments, but we are led to the conclusion that Dutton believed the movements were close to the surface.

He discussed briefly general elevations and subsidences of portions of the earth's surface. He stated very positively that the theory of isostasy offers no explanation of these changes in level. He held that the idea of isostasy means the maintenance of profiles against lowering by erosion, or raising by sedimentation. He believed that there is some other cause than isostasy

at work to make great general changes in elevation. He expressed his views on this subject in the following paragraph:

> Whatever may have been the cause of these great regional uplifts it in no manner affects the law of isostasy. What the real nature of the uplifting force may be is, to my mind, an entire mystery; but I think we may discern at least one of its attributes, and that is a gradual expansion, or a diminution of the density, of the subterranean magmas. If the isostatic force is operative at all, this expansion is a rigorous consequence; for whenever a rise of the land has taken place one of two things has happened; the region affected has either gained an accession of mass, or a mere increase of volume without increase of mass. We know of no cause which could either add to the mass or diminish the density, yet one of the two must surely have happened. But the difference of the two alternatives in respect to consequences is immense. If the increase of volume of an elevated area be due to an accession of matter, the plateau must be hoisted against its own rigidity, and also against the statical weight of its entire mass lying above the isostatic level. But if the increase of volume be due to a decrease of density there is no resistance to be overcome in order to raise the surface. Hence I infer that the cause which elevates the land involves an expansion of the underlying magmas, and the cause which depresses it is a shrinkage of the magmas. The nature of the process is, at present, a complete mystery.

Dutton's views, presented thirty-seven years ago, derived only from geologic evidence and very scanty geodetic data, stamp him with the mark of greatness. The great accumulation of geodetic and geophysical data later, and the investigations based on them, substantiate to a re-

markable degree what Dutton set forth in the Washington Philosophical Society paper, which has made him one of the outstanding men among students of the earth.

Isostasy Defined

Isostasy is a term derived from the Greek words meaning "equal standing," or "equal pressure." It is used to describe a condition of the outer portion of the earth, and is not a geological or geophysical process. Much has been claimed for isostasy as an active agent, but it is a condition of rest. It is based on some fundamental change with depth in the resisting properties of rock.

Great masses of rock stand out as mountains above plains or valley floors. At times the slopes of the elevated masses are very steep. The outstanding masses are composed of materials which are under heavy stresses tending to flatten them out, but they have been and will be prominent features in the landscape for great lengths of time. The materials have residual rigidity and strength which resist the flattening tendency. This rigidity and strength obtain, though with varying degrees, probably diminishing, from the surface down to some depth below sea-level, where a change in condition occurs. Below this materials may be rigid in the sense that they do

not yield under stresses acting for only short periods of time but they yield and conform to stresses, comparatively small ones, acting for long times, such as hundreds or thousands of years.

The resisting upper rock may be likened to wood and ice resting in water. The water conforms even to the smallest stresses or forces, while the wood and ice maintain their form. If the stresses on wood and ice are increased to a certain point they will be distorted or crushed.

Since the outer materials of the earth have some residual rigidity they will rest on the underlying masses as wood or ice rest on water. The lower material, however, is not fluid, but a viscous material. Hence the condition is more like that of light solids resting on tar or asphaltum. In any event the material of the outer portion of the earth retains its form, at least to some extent, for even geologic time, while the matter below yields and conforms to stresses resulting from the shifting of material over the earth's surface by erosion and sedimentation.

As a result of this difference in resisting power of the outer and lower material there will be a depth below sea level at which the pressures due to gravity will be the same. This depth is uniform except as affected by the increase of gravity from the equator toward the poles. Gravity being greater at the poles, a smaller thickness of

material of the same density there will equal in weight a given thickness at the equator.

This equilibrium of the outer material of the earth on the material below is called Isostasy. In view of the statements made above it is readily understood that it is a condition of rest and quiet, not one of force and movement.

There is continuous shifting of load over the earth's surface by erosion and sedimentation. This disturbs isostasy and there is a readjustment. If two rafts of logs were floating in a lake and if some logs were taken from one raft and added to the other, the hydrostatic equilibrium would be temporarily disturbed, but would soon be restored. Some water would be pushed aside from under the augmented raft and a like amount would move up under the depleted one. This phenomenon familiar to all is just about what occurs at the depth of equal pressure down in the earth; but the movement of deep material does not adjust itself so rapidly nor so completely to change of pressure above as does the water.

Years ago many thought the earth had a liquid interior with a solid shell resting on it. The outer shell was called the *crust of the earth.* The outer portion is still thought of and spoken of as the crust, but this term does not convey a correct idea of the actual earth conditions as now understood. Since the term is so firmly

established in general usage, it is thought better to continue its use rather than to invent a new one.

One of Webster's definitions of the word *crust* is: "The hard external coat or covering of anything; the hard exterior surface or outer shell; an incrustation." This definition seems to justify the continued use of the word crust to designate that portion of the outer earth which is solid and has residual rigidity and strength and which resists complete breaking down of form under gravitational stress.

Illustration of Isostasy

It is difficult at times for one to visualize the isostatic condition of the earth's crust. It may help somewhat to consider a simple illustration. Let us take equal masses of a number of different metals having different densities but none greater than that of mercury. Have the several masses of metal cast into prisms of the same cross section. All the prisms will have the same mass and the same cross section, but they will differ in length inversely as their densities. If we should place these prisms in a vessel partly filled with mercury, one alongside of the other, we should find that as each prism has the same mass, the same cross section, and will displace the same amount of mercury, the lower bases of the

several prisms will be in the same plane. The upper surfaces of the prisms will project different amounts, thus forming a very irregular surface. (See Fig. 4.) The lower surfaces of the prisms define what may be called the depth of compensation. Now, suppose we should, in imagination, cut the earth's crust into blocks by vertical planes and let the bases of these blocks be 60 miles below sea level and each 100 miles square or, if preferred, some larger or smaller

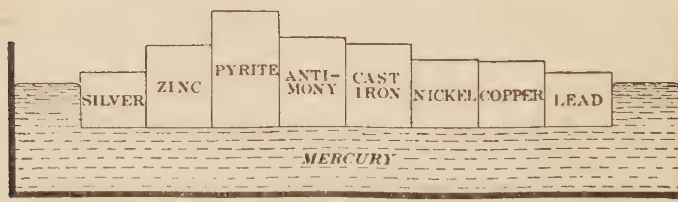


FIG. 4.—An illustration of isostasy. The blocks of metal, all lighter in density than mercury, have equal masses and cross sections. Each displaces the same amount of mercury and thus sinks to the same level as the other blocks. The upper surfaces of the blocks stand out at different heights, the lighter the block the higher it stands.

square. Let it also be supposed there is no resistance to the vertical movement of a block with relation to the adjacent blocks by reason of friction or other causes. According to the theory of isostasy each of the truncated pyramids will have the same mass, each will have the same area of its base, but the lengths of these figures will vary considerably. Therefore, the average density of the matter in each truncated pyramid

will be a function of the length of the block. We may express the above relations by a simple equation:

$$VD = C \text{ (a constant).}$$

That is, if the volume, V, of one of the blocks under consideration is greater than normal, the density, D, of the material in it must be less than normal. If the volume is less than normal, the density will be greater.

Now, suppose the truncated pyramids of the earth were placed in a liquid or very plastic substance of somewhat greater density than the earth's crust. The lower bases of the blocks would form a smooth surface, while the tops of the blocks would form an irregular surface. The blocks would project amounts inversely proportional to the density of the material in them.

The above illustration is for the isostasy of Pratt.

In Fig. 5 is illustrated the isostasy of Airy. The blocks are of copper which are floating in mercury. The longer blocks stand out higher than the shorter ones, but they also project downward farther into the liquid. This figure was used by C. R. Longwell in his excellent review of A. Born's book "Isostasie und Schweremessung," which appeared in the Jan., 1925, number of *The Geographical Review.*

Prisms of the Earth's Crust

In order to visualize the earth's crust and how adjustments are made to restore isostasy, we may conceive the crust as being composed of prisms separated by vertical planes. (See Fig. 6.) The prisms will extend to a uniform depth, and if equal in cross section they will have the same weight or mass and therefore exert the same pressure on the subcrustal matter on which they

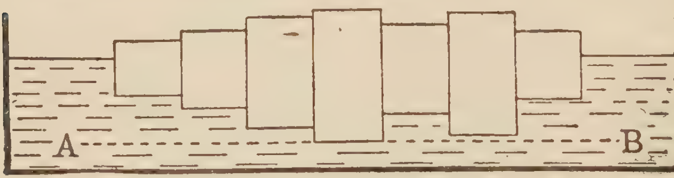


Fig. 5.—An illustration of isostasy after the Airy, or Roots of Mountains, principle. In this case the blocks are of the same material, copper, have the same cross section but different lengths; each has a different mass, hence their surfaces extend to different depths in the mercury and extend upward to different heights. This should be contrasted with Fig. 4, which illustrates the Pratt idea of isostasy. From article by C. R. Longwell, *Geographical Review,* January, 1925.

rest. The prisms are assumed to be free to move up or down without restraint from contiguous prisms. With this ideal condition a prism subjected to erosion would move upward, and the one on which sediments are deposited would move downward. The sub-crustal material would conform to the surface changes and move horizontally from below the weighted prism toward the lightened one. (See Fig. 23.)

Of course there is great frictional and shearing resistance to any vertical movements of the real crust under shifting loads at the surface, but since isostasy exists the crust must go up and down.

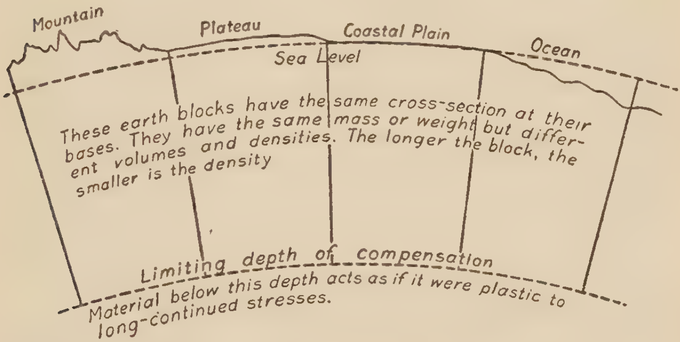


FIG. 6.—If the earth's crust should be cut into blocks of equal horizontal cross section by vertical planes, each block would have very nearly the same mass as each of the other blocks. The blocks would exert the same pressure on the subcrustal material. It is not definitely known what is the cross section of the block which may be in isostatic equilibrium independently of the surrounding blocks but it is probably of the order of magnitude of 50 or 100 miles square.

Topography Compensates Abnormal Density in Isostatic Shell

The Geographical Journal for July, 1920, contains a paper on isostasy, read by Colonel Burrard before the Royal Geographic Society.[2] In the general discussion of which at the end of the paper is a statement by R. D. Oldham in which

[2] "A brief review of the evidence on which the theory of isostasy is based," *The Geographical Journal*, July, 1920.

he emphasizes the importance of stating clearly whether mountains are compensated by the deficiency of material in the prisms under them or whether they are the compensation of the light material in the prisms. It is the writer's belief that a mountain mass is the result of the lighter material in the prism under it, rather than that the deficiency of density in the prism is due to the mountain mass. Likewise, the oceans compensate the excess of density under them. It is true that in America geodesists have spoken of compensating deficiency of material under the continents and compensating excess of material under the oceans as the result of the presence of the continental mass above mean sea level in the one case and of the ocean volume with deficient density in the second case. However, the writer wishes to go on record as being in favor of the theory that the mountains and the oceans are the result of the deficiency and excess of density, respectively, in the crustal prisms under them.

The writer believes that it will be most convenient to continue to speak of the compensation of land masses and of the deficiency of the mass in the oceans, but, with the explanation given above, the reader will not be misled into believing that the isostasist holds that the continents and oceans are the causes and the "isostatic compensation" the effect.

Shape and Size of the Earth

If the earth were not rotating and its materials were homogeneous with respect to depth —that is, if at any depth there were uniform densities around the whole earth and if the material were plastic—the actual surface of the earth would be a true sphere. This condition would be brought about by the attraction on each other of the particles composing the earth. The earth, however, is rotating and, due to the centrifugal force, the surface of the ideal earth mentioned above would be a mathematical figure called a spheroid of revolution.[3]

As a matter of fact the earth's surface is irregular, due to the heterogeneous densities in the crust and to a degree of viscosity, at least in the outer mass, which resists the tendency of the material to arrange itself in strata each with a uniform density. If the earth's materials were highly plastic, the mountains would flatten and their materials would spread over the continents, while the materials of the continents would flow out to the oceans and all irregularities in the earth's surface would disappear. The water of the oceans would then spread out over the whole earth and have the same depth at all places. This is not strictly true, for equipotential surfaces at

[3] See F. Tisserand, Traité de Mécanique Céleste, Vol. II, Chaps. VI, VII, XIII, XV, and XVIII.

different altitudes are not parallel, but the deviation is extremely small.

If sea-level canals were cut into the existing land areas of the earth, the surface of the waters of the oceans and of those connecting sea-level canals would form a figure of equilibrium very closely approximating a spheriod of revolution. The deviation of this imaginary surface from the mean spheroid of revolution would be a maximum of possibly 100 meters. The maximum deviations would occur under great mountain masses, such as the Andes, the Himalayas, and the Rockies.

It is not necessary for the student of isostasy to have a complete knowledge of the attempts through the ages to solve the great problem which has ever been before human beings as to the shape and size of the earth. Many determinations of the shape and size of the earth have been made during the past hundred and fifty years, and many more will be made as geodetic data accumulate, for we shall always be interested in obtaining greater accuracy in the derived dimensions, and to learn whether the shape and size obtained from the use of geodetic data in one continent agree with those based on the data for other continents.

The equatorial radius determined by Hayford is 6,378,388 meters with a probable error

of 18 meters (about 60 feet). This probable error is small as compared with the length of the radius. This accuracy is sufficient for all geological studies, though in isostatic and other geophysical researches an even greater accuracy is desirable.

Among the books and reports which give the various dimensions of the earth are: (1) John F. Hayford, "The Figure of the Earth and Isostasy from Measurements in the United States," U. S. Coast and Geodetic Survey; (2) John F. Hayford, "Supplementary Investigation in 1909 of the Figure of the Earth and Isostasy," U. S. Coast and Geodetic Survey; (3) William Bowie, *Special Publication No. 40,* "Investigations of Gravity and Isostasy," U. S. Coast and Geodetic Survey; (4) R. S. Woodward, "Smithsonian Geographical Tables"; (5) F. R. Helmert, "Theorien der Höheren Geodäsie"; (6) Arthur D. Butterfield, "A History of the Determination of the Figure of the Earth from Arc Measurements," Worcester, Mass., 1906. (7) Mansfield Merriman, "The Figure of the Earth," New York, 1881; (8) Captain (now Colonel) G. Perrier, "La Figure de la Terre—Les Grandes Opérations Géodésiques" in *Revue de Géographie Annuelle.* Tome II, 1908.

The Earth's Surface

The earth's surface is irregular. Of the 197,000,000 square miles of area 57,000,000 are land and 140,000,000 are water. (See Fig. 7.) The continents have mean elevations only a little above sea level; the elevation of the United States is only about 2500 feet on an average, and

FIG. 7.—The land area of the earth's surface is approximately 197,000,000 square miles of which 57,000,000 square miles is land. The area of the United States, for which intensive isostatic investigations have been made, is close to 3,000,000 square miles. Other areas involved in the isostatic investigations are greater in total area than that of the United States. Some isostatic investigations have been made by utilizing gravity observations determined at sea in a submarine. That work was done by Dr. Vening Meinesz of the Dutch Geodetic Commission.

this is about the average elevation for the whole of North America. The average elevations in feet of the continents (given in H. S. Washington's paper entitled "The Chemistry of the Earth's Crust," *Journal* of The Franklin Institute, Dec. 1920) are: North America, 1888

feet; South America, 2078 feet; Africa 2021 feet; Europe, 939 feet; Asia, 3189 feet; and Australia, 805 feet.

It is difficult to obtain an estimate of the average depths of the oceans. The depths derived would depend upon the limits chosen for the several oceans, and the surveys of the oceans are so incomplete and fragmentary that the estimates might have large uncertainties. A fair estimate of the total amount of water on the earth has been made. It has been stated by Sir John Murray that if the waters were spread out uniformly over the earth's surface the depth would be about 9000 feet, somewhat less than two miles.

The greatest elevation of land is that of Mt. Everest in the Himalayan Mountains which is 29,141 feet above sea-level. The deepest place found in the oceans is east of the Philippine Islands, where the depth is about 32,000 feet. The crest of Everest stands thus about 61,000 feet above the lowest known place in the oceans.

But in spite of the great irregularity of the solid surface of the earth, the water surface is very close to a spheroid, a regular mathematical figure. The water surface is called the geoid. From investigations covering the area of the United States it was found that the maximum deviation of the geoid from the spheroid or average surface, is only about 19 meters (62

feet). No determinations have been made of the difference between the two surfaces in other countries, but it is believed that the maximum deviation, which should be found under the Himalayan and Andes mountains, is not greater than 100 meters (about 330 feet).

Relation Between Spheroid and Geoid

The geoid is the form which would be taken by the surface of the oceans undisturbed by meteorological conditions and the tidal forces of the sun and moon. If sea-level canals were extended over the continents, the average position of the surface of the water in them would coincide with the geoid. The water surface over the oceans and in the continental canals would at all places be at right angles to the plumb line or resultant direction of the attractive force exerted by the earth's materials, including the water of the oceans, combined with the centrifugal force due to the earth's rotation.

Owing to the irregular surface of the earth the geoid surface is irregular. It inclines upward from the oceans toward the continents and large islands. (See Fig. 8.) Within a continent it inclines upward from a valley toward a plateau or mountain.

It is impracticable to obtain equations for the surface of the geoid, due to lack of data. Besides,

if sufficient data were available, and equations were derived, it would not be convenient to make use of the geoid in the computations for the geographical positions of objects; but it is practicable to derive a mathematical surface, a spheroid, which will be a close approach to the

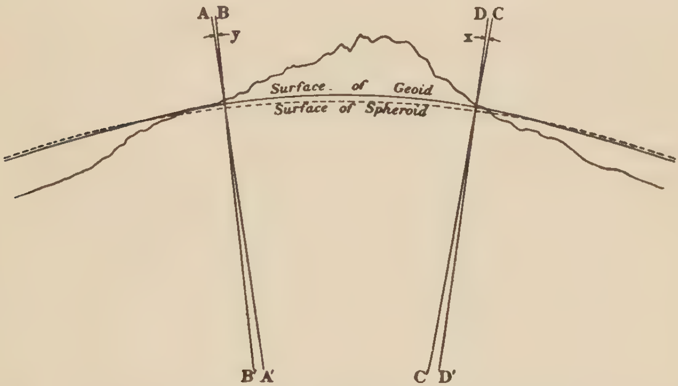


FIG. 8.—The surface of the waters of the ocean and of water in sea level canals, extended in imagination through continental areas, forms the geoid. It is irregular to the extent of having elevations or depressions as great as 100 feet. The elevations occur under land masses, especially islands and mountain systems. The depressions occur under valleys and over deep parts of the oceans. The average or mean surface of the earth is called the spheroid. It is derived from a combination of triangulation and astronomic data. The shape of the spheroid surface, but not its dimensions, can be determined by means of gravity data.

geoid. For the area used in computing the spheroid the geoid surface will extend above the spheroid in some places and fall below it in others.

Deflections of the vertical are derived from the differences between astronomic and geodetic

latitudes and longitudes. These deflections enable us to compute the inclination of the geoid surface to that of the spheroid. It is well known that the plumb line, to which astronomic observations are referred, is deflected toward land masses and away from large bodies of water. Notable examples of this are found on the island of Porto Rico and in Turkestan. In the former the plumb lines at Ponce and at San Juan are drawn together 56 seconds, corresponding to a distance of about 1 mile on the earth. These two places are only 33 miles apart in the north and south direction. Deep water lies both to the north and south of this island.

The other notable deflection of the vertical is in a valley in Turkestan. The distance between two astronomic stations which are connected by triangulation is 65 miles in the north and south direction. The plumb lines at these two stations are drawn away from each other by 76 seconds, corresponding to almost 1½ miles on the earth. To the north and south of the valley are mountains which cause the disturbance.

The method employed in computing the deviation of the geoid from the spheroid is set forth on pages 57–65 of "The Figure of the Earth and Isostasy." If the deflection of the vertical or tilting of the geoid surface is 20 seconds of arc at a station where the geoid and spheroid surfaces intersect, and should this tilt-

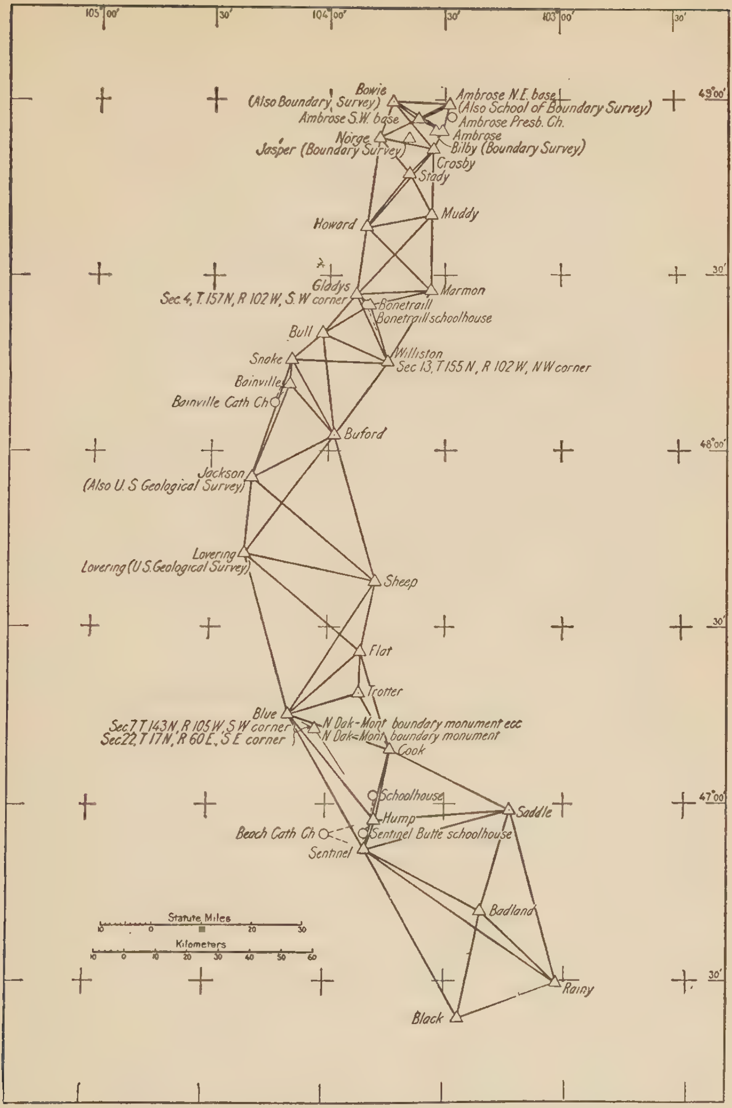


FIG. 9.—An arc of triangulation along the 104th meridian in the United States. It is by triangulation and connected astronomic data that we have deflections of the vertical which make possible one line of attack on the determination of abnormal densities in the outer portion of the earth.

ing continue without change for 40 miles, the two surfaces at the latter place would be 20 feet apart. The two sides of an angle of one second deviate 1 foot at 40 miles.

Along an arc of triangulation there are usually many stations at which the deflection of the vertical has been determined. Therefore, the larger variations of the geoid surface can be computed. A simple method is to assume that the tilting of the geoid at a station continues one-half the way to the next deflection station.

Let it be assumed that in an arc of triangulation there are a number of deflection stations exactly 40 miles apart. Let the stations be numbered 1 to 10 and let the midway points be numbered the same as the preceding station with the letter "a" added. In the second column of the table following are given deflections of the vertical. Let it be assumed that the plus deflections indicate a tilt upward of the geoid surface in the direction of the increase in the numbers. The changes in the distance between the geoid and spheroid surfaces are shown in the fourth column, and the accumulated change is shown in the last column:

Station	Deflection	Change between surfaces		Accumulated change between surfaces	
		From station, to station	Amount	At station	Amount
			Feet		Feet
1	+ 4	. . . .	. . . .	1	0
		1 — 1a	+ 2		
2	+ 8	1a — 2	+ 4	2	6
		2 — 2a	+ 4		
3	+12	2a — 3	+ 6	3	16
		3 — 3a	+ 6		
4	+16	3a — 4	+ 8	4	30
		4 — 4a	+ 8		
5	+24	4a — 5	+12	5	50
		5 — 5a	+12		
6	+18	5a — 6	+ 9	6	71
		6 — 6a	+ 9		
7	−10	6a — 7	− 5	7	75
		7 — 7a	− 5		
8	0	7a — 8	0	8	70
		8 — 8a	0		
9	+20	8a — 9	+10	9	80
		9 — 9a	+10		
10	+40	9a — 10	+20	10	110

CHAPTER II

QUANTITATIVE TEST OF ISOSTATIC THEORY

THE United States Coast and Geodetic Survey has extended triangulation along the Atlantic, Gulf, and Pacific coasts of the country, and in the interior to connect the coasts. In addition, that Bureau has determined the astronomic latitude, longitude, and azimuth at hundreds of triangulation stations. Much of the data for that work had been collected by the time John F. Hayford assumed charge of the geodetic work of the Bureau in 1899; but the triangulation was not a unit. It had been started at a number of places along the coasts and for each place some local astronomic station was used as the point from which to compute the geographic positions of the triangulation stations. This system was satisfactory until the extension of the triangulation brought the several systems into contact. Then there were found to exist gaps, overlaps, and offsets. All of these had to be eliminated before the triangulation system of the country could be used for figure of the earth investigations. This coördination was done by Hayford with the assistance of his highly trained asso-

ciates in what was then known as the Computing Division of the Bureau (now a part of the division of geodesy). The amount of work to recompute and readjust the triangulation system of the country and to compute the positions of the triangulation stations from a single station was enormous. But it had to be done for the use of those engaged in the surveying and mapping of the country, and for perpetuation of the location of our international, state, and county boundaries. It had an immense practical value as well as a scientific one.

As the triangulation computations progressed, Hayford and his associates attacked the problem of determining the attractive effect of the earth's irregular surface on the direction of the plumb line at each of several hundred triangulation stations at which astronomic observations had been made. These computations included the effect of masses above sea level and deficiencies of mass in the Atlantic, Gulf, and Pacific, which were within 2564 miles of each station. In order that this might be done by the comparatively small personnel available, and within a reasonable time, Hayford devised ingenious methods for quickly reading the topographic maps and for making the computations. He realized that a figure of the earth derived from deflections of the vertical data would have greater accuracy if corrections for the deficiency

of mass under land masses, and excess of mass under water areas, were applied to the astronomic data. The effect of the crustal abnormalities would be to offset to some degree the attractive effect, positive or negative, of the topographic features. Therefore, in his plan he included the computation of the isostatic compensation of the topography.

Assumptions as to Isostatic Compensation

To make the application of the theory of isostasy at all feasible in his figure of the earth investigations Hayford had to make certain assumptions of general applications. These were:

(1) That the isostatic compensation of topographic features is complete.

(2) That each topographic feature, no matter how small in horizontal extent, is separately in equilibrium.

(3) That the compensation of the topographic feature is directly under the feature.

(4) That the compensation is uniformly distributed vertically.

(5) That the compensation extends to a certain depth, and that this depth is the same for all parts of the crust. This is called the depth of compensation.

These are artificial assumptions, one may say, but how else could the work have been done? In spite of the fact that Hayford made his tests twenty years ago, no one, not even the most vigorous opponent of isostasy, has made an exhaustive analysis along other lines of the geodetic data used by him, nor has there been advanced any other scheme or plan for doing so.

The degree to which these assumptions are effective is shown by the way their application reduced the outstanding difference between the astronomic and geodetic latitudes, longitudes and azimuths. This subject is discussed elsewhere in this publication.

The same assumptions made by Hayford were later used by him and the writer in their test of the theory of isostasy by gravity data and later by the writer alone. While they were necessary to simplify the computations neither Hayford nor the writer believed them to be strictly true. There must, from the nature of the case, be some variation in the depth of compensation from one part of the crust to another and it is inconceivable that each small feature is independently in equilibrium; that everywhere compensation is exactly complete; that all the compensation is directly below the feature; or that the compensation is uniformly distributed vertically.

By the use of the assumptions, however, it was possible to prove that the theory of isostasy is

true to a remarkable degree, as is shown in other places in this book. What remained to be done was to work out the details and in this much has already been accomplished.

Methods Employed in Making the Isostatic Tests

A detailed description of the method of using deflections of the vertical in testing isostasy is given in the "Figure of the Earth and Isostasy," by J. F. Hayford, U. S. Coast and Geodetic Survey, 1909. In it are shown the derivations of the formulas used, and how the effect of the topography and its compensation for various depths is computed, out to a distance of 2564 miles from each station. There are also described the methods by which the most probable depth of compensation, and the dimension of the spheroid, are derived.

The methods of testing isostasy by means of values of gravity on land and sea are described in detail in *Special Publication No. 10,* of the Coast and Geodetic Survey, by J. F. Hayford and William Bowie, 1912. In that report are given the formulas used in the tests, and the tables for computing the effect of topography and compensation for the zones into which the whole surface of the earth is divided. The report contains many tables in which are given

data for the three methods used for making gravity reductions; namely, the Free Air method, in which the effect of topography and compensation are not considered; the Bouguer,

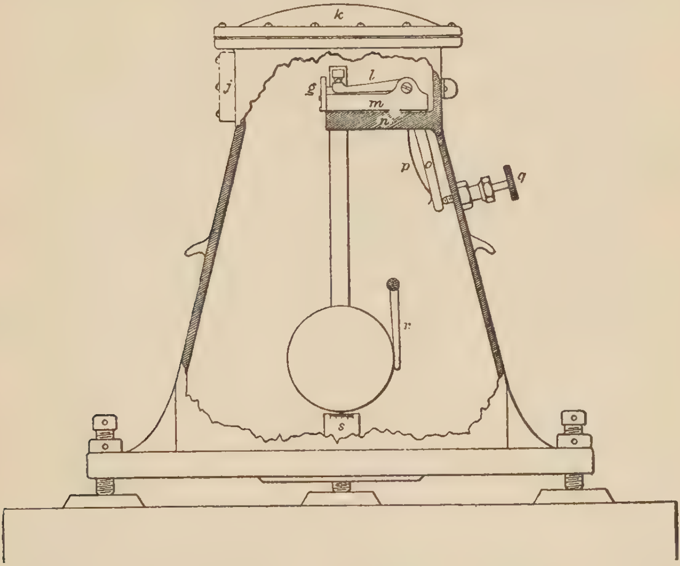


FIG. 10.—The interior of the pendulum case, showing the pendulum in position. Partial vacuum, 60 mm., is created in the case during the swinging of the pendulum. A plane in the head of the pendulum rests on the knife edge in the support. The pendulum, started with a total amplitude of 8 mm., has an amplitude of between 2 and 3 mm. after twelve hours' swinging. The oscillations of the pendulum are compared with the beats of a chronometer or clock by the coincidence method.

in which only the effect of topography is employed; and the Isostatic, in which the effect of both topography and compensation are applied.

In *Special Publications Nos. 12* and *40,* of the Coast and Geodetic Survey, are shown the

methods for deriving the flattening of the earth, and in the latter the method of deriving the most probable depth of compensation.

A complete work on Isostasy would contain practically all the contents of two reports on the use of deflections in testing isostasy, and of four reports on the testing of isostasy by gravity data. It is beyond the scope of this book to cover in detail the methods employed and the tests made. Besides, those desiring to make similar tests, and to study the methods intensively, can secure the essential reports of the U. S. Coast and Geodetic Survey, bearing on the subject, from the Superintendent of Documents, Washington, D. C.

Reliability of Geodetic Data

There has been doubt in the minds of many geologists and geodesists as to the reliability of the data used in the isostatic investigations and of the conclusions that have been reached. The isostatic investigations involve both observations and computations. The observations are accurate beyond doubt; in fact, they are more accurate than are necessary in carrying on the investigations. For instance, it is quite certain that the error of an observed deflection of the vertical is seldom greater than 0.″5 of latitude or longitude, and the error of an observed intensity of gravity is seldom greater than 0.003 or 0.004 dyne. We may conclude, therefore, that the ob-

served data are correct. They are accurate physical measurements.

The method used in computing the effect of topography on the deflections of the vertical and the accuracy of the computations are discussed in much detail in Hayford's books on the figure of the earth and isostasy already referred to. The accuracy of the computed topographic effects as applied in the gravity reductions is discussed fully in *Special Publication No. 10*. It is not necessary to quote from these publications, since they are readily available to any one who wishes to study in detail the question of the accuracy of the topographic corrections. The writer believes that he is justified in stating that these topographic corrections can be accepted as reliable and accurate.

If we accept the statement that the observations and the computed topographic corrections to the deflections of the vertical and to the intensity of gravity are correct to the required degree of accuracy, then there is left only the question of the reliability of the isostatic corrections.

Accuracy of Computation of Isostatic Compensation

When geodetic measurements were corrected for the visible land masses and the deficiency of material in the oceans, there were outstanding

differences that showed decided relations to the character of the topography in the vicinity of the various stations. Isostasy was the theory advanced to explain the presence of these outstanding differences. In order to make the computations to test the theory of isostasy, some simple method had to be adopted. The most logical method seems to be the one used first by Hayford and since by others working in the geodetic field. The method is based on the assumptions that isostasy is complete; that the compensation is directly under the topographic feature, whether land or water; that the compensation is uniformly distributed vertically; and that it extends from the surface of the earth to a uniform depth below sea level.

Computations were made on this theory to obtain the effect of the isostatic compensation on the deflection of the vertical and on the intensity of gravity. The computations were made, first, for a number of deflection stations in the United States, then for several in India, and later for gravity stations in the United States, Canada, Europe, and Asia.

The corrections for isostatic compensation as thus computed were applied to the deflections of the vertical and to the values of gravity with the remarkable result that for the area of the United States deflection anomalies were on an average reduced to 10 per cent of what they

would be if there were no isostatic compensation and the average gravity anomaly to from 10 to 15 per cent of what it would be on the rigid-earth hypothesis. These results indicate very clearly that the United States, both as a whole and locally, is in practically complete isostatic adjustment and that the computation of the isostatic effect is substantially correct.

Prediction as a Test of the Theory of Isostasy

In a recent article,[1] entitled "A brief Review of the Evidence on which the Theory of Isostasy is Based," Colonel Burrard brings out a number of interesting points in connection with the subject. He shows how the isostatic method of computing the effect of topography and compensation enables one to predict with considerable accuracy the value of gravity at any particular station, and he shows that this can not be done by any other method.

If we can predict the value of the deflection of the vertical or the value of gravity at a station and find when the observations are made, a difference between the predicted and observed values, or an anomaly, only 10 or 15 per cent as large, on an average, as it would have been if the prediction had been made with the rigid-

[1] *The Geographic Journal,* Royal Geographic Society, London, July 1920, p. 47.

earth theory, then we may say that we have arrived at a theory that is workable and reasonable. The methods adopted by the geodesists can stand the test of prediction. Some other method not yet formulated may do equally well, but it can not depart materially from the one now in use.

Extent of the Isostatic Tests

The first comprehensive quantitative test of the theory of isostasy was made with 265 deflections of the vertical in the meridian and 241 deflections in the prime vertical in the area of the United States. A deflection in the meridian is the difference between an astronomic latitude and the latitude at the same point determined by triangulation. A deflection in the prime vertical is derived from the difference between an astronomic and a triangulation longitude, or between an astronomic and triangulation azimuth. The astronomic latitudes, longitudes, and azimuths are affected by the irregular surface of the earth and abnormal densities of crustal material.

The report of the first test appeared in 1909. A second test involving 381 deflections in the meridian, and 384 deflections in the prime vertical in the United States was made immediately after the first one, a report on it appearing in 1910. These two tests were made by the late J.

F. Hayford, of the U. S. Coast and Geodetic Survey.

In September, 1909, Hayford presented to the International Geodetic Association a short paper giving the results of the application of the theory of isostasy to the reduction of 56 gravity stations in the United States. The results were in accord with those obtained when the theory had been applied to reductions of deflections. Then followed investigations involving gravity stations in a number of widely separated areas of the earth.

The tests have now become quite general and with each additional area used the isostatic idea has been strengthened. It seems safe to assert that the *theory of isostasy* has been proven and it may now be spoken of as the *isostatic principle.*

The following table gives the essential data for the gravity stations for which reductions have been made by the isostatic method. The detailed data for these stations are published in the reports and papers whose titles are given in the foot-notes on page 51.

A disk of material with a density of 2.67, of great horizontal extent and 30 feet in thickness, will affect the value of gravity 0.001 dyne. It requires a deficiency or excess of matter below a gravity station equivalent to a layer 600 feet in thickness to affect gravity 0.020 dyne and equivalent to a layer 900 feet in thickness to

DATA FOR GRAVITY STATIONS REDUCED BY THE ISOSTATIC METHOD

Place	No. of stations	Depth of compensation used	No. of positive anomalies	No. of negative anomalies	Maximum anomaly	Mean anomaly: With regard to sign	Mean anomaly: Without regard to sign
					Dyne	Dyne	Dyne
1. United States	296	113.7	126	168	−0.093	−0.006	0.021
1. Southern Canada	42	113.7	13	29	−0.045	−0.009	0.013
2. Mackenzie Valley, Northern Canada	9	113.7	4	5	+0.021	+0.001	0.010
3. India	73	113.7	37	35	−0.078	−0.004	0.023
4. Spain	31	113.7	21	10	+0.077	+0.009	0.032
1. Region of Alps	27	113.7	19	8	+0.049	+0.014	0.021
5. Western Siberia	8	113.7	2	6	−0.025	−0.005	0.007
1. St. Paul and St. Michael Islands, Alaska	2	113.7	1	1	+0.010	+0.004	0.006
6. Atlantic Ocean, Holland to Gibraltar	10	113.7	10	0	+0.089	+0.044	0.044
6. Mediterranean Sea	15	113.7	11	4	+0.129	+0.038	0.044
6. Red Sea and Indian Ocean	21	113.7	11	10	−0.087	+0.004	0.036
7. Islands in South Pacific Ocean, Lat 15 deg. S., Long. 165 deg. E.	5	113.7	4	1	+0.059	+0.030	0.030
8. Norway	46	113.7	33	13	+0.129	+0.016	0.027

affect gravity 0.030 dyne. The maximum anomaly on a continent for stations considered in the above table is —0.093 dyne. This may be caused by a deficiency of mass equivalent to about 2800 feet. There are two anomalies of +0.129, one on the Mediterranean Sea and the other on an island off the coast of Norway. Each could be caused by an excess of mass of about 4000 feet. It is seen that even the larger anomalies do not require a mass comparable in amount to the masses present in the great mountain systems.

The means, without regard to sign, are quite small as compared with what the mean anomalies would be if the irregular surface of the earth were not considered compensated.

If the means for the several groups in the above table are considered as if they were for single stations, we should have 9 positive and

1. *Special Publication No. 10*, by J. F. Hayford and William Bowie; *Special Publications Nos. 12*, 1914; *40*, 1917; and *99*, 1924; by William Bowie, all of the U. S. Coast and Geodetic Survey, Washington.

Each of five groups of stations close together was considered as a single station in taking means, etc., and two stations had zero anomalies. There are now in the United States 308 gravity stations, for which data are available.

2. "Gravity in Northwestern Canada," *Publications of the Dominion Observatory*, Vol. VIII, No. 6, Ottawa, 1924; and "Gravity Results in the Mackensie Basin," *Journal of Royal Astronomical Society of Canada*, Nov.–Dec., 1923, both by A. H. Miller.

3. *Prof. Paper No. 15*, by H. J. Couchman, Survey of India, 1915.

4. "La Reducción Isostatica de Neustras Estaciones de Gravidad," by Guillermo Sans Huelin, *Memorias del Instituto Geographico y Catastral*, 15, 1926. And *Amer. Jour. of Science*, Oct. 1926, review of above article by William Bowie.

5. "Isostasy in Western Siberia," by William Bowie, *Amer. Jour. of Science*, Vol. 21, February, 1926.

6. "Isostatic Reduction, by the U. S. Coast and Geodetic Survey, of the results of the Pendulum Observations at sea made in 1923 between Holland and Java." *Pub. of the Dutch Geodetic Committee*, 1926.

7. "Isostasy in the Southern Pacific," by William Bowie, *Journal*, Washington Academy of Sciences, Vol. 15, No. 20, 1925.

8. "Untersuchungen über Schwerkraft und Isostasie," by W. Heiskanen, Publication of the Finnish Geodetic Institute.

4 negative anomalies. The means, with and without regard to sign, would be +0.010 and 0.024, respectively. If the 3 groups of sea stations are omitted there would be 6 positive and 4 negative anomalies. The means, with and without regard to sign, would be, respectively, +0.005 and 0.019.

Of the 27 Alps stations, 8 have anomalies above 0.030, while 16 of them have anomalies below 0.020.

There are 7 stations in the Indian Ocean above depths of water between 2100 and 2400 fathoms. The maximum anomaly for these stations is —0.016. There are 2 positive and 5 negative anomalies. The mean anomalies, with and without regard to sign, are, respectively, —0.005 and 0.010.

It cannot be said that the sea stations in the three groups considered in the above table truly represent the isostatic condition of the crust under ocean areas. Many of the stations are close to the coast and they have the larger anomalies. The writer is inclined to think that the anomalies for sea stations far from land would, in general, be smaller than the average of those considered above.

There are 585 gravity stations considered in the above table. They are scattered over a large range in longitude and in latitude from 22 degrees south to nearly 71 degrees north. The data

now at hand seem ample to test the isostatic condition of the earth's crust. The results of the test justify one in the conviction that the *theory of isostasy* has been changed to *principle of isostasy*.

CHAPTER III

ASSUMPTIONS UNDERLYING COMPUTATIONS OF ISOSTATIC EFFECT

Datum Used for Computing the Effect of Topography and Compensation

It has been held that errors have been made in the isostatic reductions as a result of having adopted mean sea-level as the datum for computing the topographic and compensation corrections instead of having adopted some other plane of reference as, for instance, the bottom of the ocean or the bottom of the sedimentary rocks. It may be well to point out here that there would be slight changes in some of the gravity anomalies if the datum plane were changed from sea-level to some other depth, say several miles below.

The same reasoning that is used on page 57, in connection with the distribution of isostatic compensation vertically and its effect on the intensity of gravity and the deflection of the vertical, will apply equally well to this question of the datum plane. With mean sea-level as the plane, the average density of the material in the prisms which are under the coastal plains is

assumed to be normal, and the density of the material under the oceans is greater than normal and under the continents less than normal. We can just as readily use a datum plane below sea-level, even at a depth equal to the greatest depth of the ocean. Then we should have to assume that the material in the prism under the deepest part of the ocean had normal density and that all other prisms have abnormally light density. Which is more logical, to assume densities lighter than normal in practically all of the outer portion of the earth or to assume that the density is less than normal for a part and greater than normal for the remainder?

In an article[1] on the hypotheses of isostasy Prof. W. D. McMillan favored the depth of 9,000 feet below the present sea-level as the datum to which all of the computations should be referred in treating the effect of topography and isostatic compensation. This is the depth, according to McMillan, to which the earth would be covered with water "if the solid portion of the earth were altogether lacking in rigidity and if the concentric layers were homogeneous in density."

Possibly this depth of 9,000 feet would be a more logical one than mean sea-level, but mean sea-level is something that we can use in a practical way. It is the surface of the water of

[1] *Journal of Geology,* February–March, 1917.

the oceans, and elevations on land can be easily referred to it. As a matter of fact, any equipotential surface of the earth or above it could be used as the datum for the computation of the effect of topography and isostatic compensation, but it is believed that the results would be the same as those obtained by the use of mean sea-level as the datum.

Density of Material Between Earth's Surface and Depth of Compensation

There has been much confusion as to just what is the stand of the isostasists in regard to densities in the earth's crust. In isostatic investigations there is no need to use a numerical value for the average density of the materials of the earth's crust for any prism. What is attempted is to weigh by indirect methods the differences in mass or deviations from the normal average density of the various imaginary prisms into which the crust may be divided. For instance, if D represents the average density of the crust under the coastal plains, then the average density of the material of the crust under the land masses is less than D and under the oceans is greater than D.

There are certain normal or average densities for the various zones or layers of material below sea-level, and isostasists are concerned simply

with the deviation from these unknown normal densities. It is generally accepted that the density of the earth increases with the depth, but it is readily seen that, as far as the computation of the effect of isostatic compensation is concerned, only the deviations from the unknown normal density need be considered.

Isostasy is based on the idea that the mean density of a unit prism of the earth's crust times its volume is a constant, and therefore that the mean density of these prisms of the same cross section, all extending to a certain depth below sea-level, will vary inversely as the volume. Consequently, under a mountain mass the prism will be longer, the volume greater, and the density less than normal; under the coastal plain the density and volume will be normal; and under an ocean the prism will be shorter, the volume less, and the density greater than normal. From the geodetic evidence we must conclude that these conditions are substantially true.

Distribution of Compensation

Uniform Distribution Vertically

It is more logical to think that the compensation is distributed through a long prism rather than through a very short one, or through a very short section of a prism, say, 5, 10, or 20 miles

in length. In a small volume it would require a rather decided decrease or increase from normal densities, especially in prisms under high mountains or deep oceans. We might assume that the compensation is nearly all confined to a certain part of the prism with other parts receiving much smaller amounts, but the computations show that no matter how the compensation is assumed to be distributed its center of gravity must be approximately 40 kilometers below sea-level in order that the computed corrections may reduce the gravity and deflection anomalies to the extent that they are reduced by the uniform distribution.

Upper and Lower Limits of Compensation

Probably we shall never be able to determine whether or not the compensation of topography is distributed uniformly with regard to depth, and we may not be able to learn what are the limits of the compensation layer, but it would seem to be logical that the compensation is distributed from some point not far below the surface down to the limiting depth of the crust.

The areas that now stand above sea level as continents and islands have been below sea-level at one or more times in the geological past. They are now in isostatic equilibrium, and that equilibrium requires a deficiency in density in the

crustal material below them. Some process must have been operating to cause the lighter density. Does it not seem more reasonable to assume that the whole thickness of the crust—or nearly all of it—should be affected rather than that the deficiency of density should occur only in a very thin layer.

As far as horizontal distribution of density is concerned, it seems more probable that whatever action was going on below the uplifted areas was not confined to very small prisms of the crust, but that it probably affected rather large ones. Much of the uplift has occurred where previously there had been heavy sedimentation. It would seem that the increase of volume and decrease of density were results of the laying down of sediments and the sinking of the crust under the weight of the added load.

It is probable, therefore, that if a large area which had once been subjected to sedimentation were affected by a change of volume below, the change would be more or less regional in its nature. It would seem, for instance, that a mountain peak like Mt. Shasta, or Pike's Peak, is not held in its elevated position by a deficiency of material extending in a small prism from the earth's surface down to the depth of compensation, about 60 miles below sea-level. It is more probable that the individual mountain peaks and their bases are supported regionally. How far re-

gional compensation extends is not known, but probably not more than 25 to 50 miles radially around the topographic feature.

Since the surface configuration is compensated by a deficiency of density below continents and islands, and by an excess of density under oceans, and since for any particular area those deviations from normal densities have probably been due to some process that has operated in recent geological times, we must conclude that the compensation could not extend out to the solid surface of the earth. Such process as may have changed an ocean area to a mountain system or plateau, or a portion of the continent to an inland sea or a continental shelf, was probably due to thermal expansion or contraction supplemented by chemical and physical changes initiated by changes in the temperature of the crustal material. Such changes of temperature would have been caused by the pushing down of crustal material under the weight of sediments, and the pushing up of crustal material by isostatic adjustment where surface material had been eroded away.

If any block of the earth's crust were subjected to a uniform change in temperature the thermal contraction or expansion, as the case might be, would be very nearly uniform from the upper to the lower surface of the crust. But such changes in temperature are probably not uni-

form throughout, at least not under an area of sedimentation. The sedimentary material that is now deposited at the surface may be several miles below sea-level some millions of years from now, as the sedimentary bed thickens. While the earliest sediments of an area would go down to a hotter region, the last of the sedimentary material would not have any change of temperature whatever as a result of the sinking of the crust under sedimentation. The average change in temperature of the sedimentary material would be one-half the increase of the first sediments laid down. On the other hand, all of the material of the crust below the sediments would have sunk to a depth approximately equal to the thickness of the sediments. Therefore, if the temperature gradient is the same from the surface to the bottom of the crust, each part of the crust that has been pushed down, excepting the overload of sediments, would have been increased in temperature a uniform amount. All of the original crustal material would expand uniformly, due to ordinary thermal action, but since there must be a cause of expansion in addition to thermal expansion, it is possible that different amounts of expansion occur at different depths. The chemical or physical re-action is probably a function of depth and pressure, and while a change of temperature of 200 or 300 degrees centigrade at a certain depth in the earth's

crust might make the material reach a critical temperature with resulting physical or chemical changes, a like change in temperature might not start chemical or physical reaction in the crust at a different depth.

It would seem necessary to limit the zone of compensation between the lower limit of the crust and the depth to which the recent sediments extend in an area of recent sedimentation. For instance, under such a region as the Indo-Gangetic plain, we should expect the compensation not to begin at a higher elevation than the bottom of the recent sediments over that plain. It seems possible, and even probable, that the compensating deficiency of density may not occur until a depth of ten or more miles below the earth's surface is reached. The critical temperatures at which chemical or physical reactions might take place may not be reached in the outer layers.

The study of geodetic data in mountainous regions may give some idea as to the depth at which the compensation may begin. It is evident that values of gravity on a comparatively flat area do not lend themselves to the determination of the variations in the depth of compensation, or of the depth at which the compensation begins. On the other hand, in a mountain region where there is much topography to be compensated, a comparatively small change in the

assumed depth of compensation and in the upper limit of the compensation should have noticeable effects on the computed values of gravity. The gravity values in mountainous regions are sensitive to the vertical shifting of the compensation layer.

An investigation bearing on this subject is now under way in the office of the U. S. Coast and Geodetic Survey, and a printed report on it should appear in the near future.

Horizontal Distribution of Compensation

The distribution of the compensation horizontally with relation to the topographic features has received attention from those geologists who hold that the earth's material is very rigid and capable of withstanding great loads. It has also received the attention of geodesists who have computed the effect of several horizontal distributions of the compensation of topographic features. It can not be said that any very definite conclusions have been reached in this matter, as from the nature of the case mathematical treatment can not give very accurate results. At the same time the evidence is all in favor of limiting the horizontal distribution within a reasonably short distance. When the compensation is distributed horizontally to a distance of 100 miles in all directions, the gravity

anomalies become more discordant than when distributed close to the feature.[2]

It is difficult to see why a plain 100 miles from a mountain should help bear the mountain mass. The mountain mass is not picked up bodily and placed on the earth's crust, but it is formed from the crust, and whatever caused the uplift acted locally rather than regionally. Of course, no one would hold that all of the compensation of a single mountain peak or ridge is located directly under it and confined within the base of the mountain peak or ridge. The compensation naturally extends out some distance, but that it extends for hundreds of miles around each large topographic feature is beyond the possibilities. Such an assumption would certainly cause the computed anomalies to be large. We may infer from the geodetic data available that the compensation is distributed locally under the topographic feature or to a distance not greater than about 100 miles in all directions.

McMillan[3] made the statement that:

> From a purely mathematical point of view any set of a finite number of observations of the intensity and direction of gravity can be satisfied not approximately but exactly in infinitely many ways by a proper distribution of the density in the earth.

[2] William Bowie, "Investigations of Gravity and Isostasy," U. S. Coast and Geodetic Survey *Special Publication No. 40,* and "Our present knowledge of isostasy from geodetic evidence," *Journal of Geology,* July–August, 1917.

[3] *Journal of Geology,* February–March, 1917.

This statement is justified mathematically, but any distribution of the densities that would exactly eliminate the anomalies of the deflections of the vertical and of the intensity of gravity but that would not be general in its application would be so artificial as not to be reasonable. The writer believes that the only hypothesis that will carry weight is one that will be very general in its application. We can not assume one depth of compensation for one station or a general group of stations, another for a second group of stations, and so on through the list, nor can we assume different distributions of densities horizontally and vertically for different stations or groups of stations. This would be merely guesswork, for no one can really tell with certainty what variations there are in the isostatic shell of the earth, except in so far as they may be indicated by borings and by the exposed rocks. McMillan is correct in saying that any general system that applies uniformly can be used only as a first approximation to the actual situation, and that "depth of compensation" and size of the "areas of compensation" depend for their successful determination on the vastly more difficult matter of second and higher approximations, and that these approximations can be obtained, if at all, only by a very much more dense net of observations.

We must remember that the first approxima-

tion eliminates nearly all of the anomalies, and the second and higher approximations are needed only to perfect the details. They are not necessary in the establishment of the truth of isostasy. The first approximation has done this.

The isostatic method used by Hayford, Burrard, and the writer, and accepted by many others, is certainly correct in its general principles and is a long step in advance in geophysical science. It is probable that the exact depth of the compensation and the exact area over which the compensation of a feature is distributed can never be determined with mathematical precision even for local areas. There will always be an error in the result, the size of which can not be determined. The writer believes that further refinement of the observations is unnecessary, because the outstanding anomalies in deflection and gravity work are large in comparison with the probable errors of the observational data. The deflection and gravity data are undoubtedly sufficiently accurate for all studies connected with isostatic compensation.

Horizontal Location of Compensation

Tests which have been made indicate that the gravity anomalies are as completely eliminated by distributing the compensation of the topography which is close to a station uniformly to a

distance of about 60 kilometers from the station as by assuming the compensation immediately under the separate topographic features. The gravity anomalies are increased somewhat if the compensation is distributed to a distance of 166 kilometers from the station.

In making the tests only stations in mountainous areas were used. It is evident that there could be nothing disclosed by the use of stations which are on comparatively level ground for if in a circle of 166 kilometers radius the elevation of the topography were nearly uniform, there will be the same amount of compensation under each unit area of the circle regardless of whether the compensation of each irregularity of the topography is considered to be directly under it, or uniformly distributed under the total area of the circle.

Apparently, there is no way by which we may determine with certainty whether the compensation is directly under a topographic feature, or distributed around it to a limited distance. The distance from the center of gravity of the compensation to the station will be approximately the same in each case, and the cosine of the angle formed by the vertical through the station and the line from the station to the center of gravity of the compensation will be nearly unity. The vertical component of the compensation will, therefore, be nearly the same for the local and

for the regional distribution to moderate distances.

When the compensation of a topographic feature is distributed for a distance as great as 166 kilometers the above does not hold true, for then the vertical components of the effect of the compensation will be quite different in the two cases, owing to the difference in the distances from the station to the centers of gravity of the compensation, and to the large difference in the vertical angles.

Computation of Effect of Local Deviations of Density on Gravity

Tables have appeared in U. S. Coast and Geodetic Survey *Special Publications Nos. 10, 12,* and *40,* and in *Professional Paper No. 17* of the Survey of India, by which one can compute the effect of certain masses on the value of gravity. An extension of these tables is given on page 69.

The use of the above table is facilitated by Fig. 14. The horizontal distances from the station, shown as a dot at the center of the top line, are in miles and the depths are in feet. The values of the attraction given in the table are in dynes. One one-thousandth of a dyne corresponds to one part in one million of the earth's attraction. The density of the material was taken as unity in computing the table. In order to get

Attraction of cylindrical blocks.

(Station at center of upper surface. Density = 1)

Depth of block	Radius of block in miles														
	½	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½
Feet	Dyne	Dyne	Dyne	Dyne	Dyne	Dyne	Dyne	Dyne	Dyne	Dyne	Dyne	Dyne	Dyne	Dyne	Dyne
1,000	0.010	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.013	0.013	0.013	0.013	0.013	0.013	0.013
2,000	.017	.021	.022	.023	.024	.024	.024	.025	.025	.025	.025	.025	.025	.025	.025
3,000	.021	.028	.031	.033	.034	.035	.035	.036	.036	.036	.036	.037	.037	.037	.037
4,000	.024	.034	.039	.042	.044	.045	.046	.046	.047	.047	.048	.048	.048	.048	.049
5,000	.025	.038	.045	.050	.052	.054	.055	.056	.057	.058	.058	.059	.059	.060	.060
6,000	.027	.042	.051	.056	.060	.062	.064	.066	.067	.068	.069	.070	.070	.071	.071
7,000	.028	.045	.056	.063	.067	.071	.073	.075	.077	.078	.079	.080	.080	.081	.082
8,000	.028	.047	.060	.068	.074	.078	.081	.084	.086	.087	.088	.090	.091	.091	.092
9,000	.029	.049	.063	.073	.080	.085	.089	.092	.094	.096	.098	.099	.100	.101	.102
10,000	.029	.051	.066	.077	.085	.091	.095	.099	.102	.104	.106	.108	.110	.111	.112
12,000	.030	.053	.071	.084	.094	.102	.108	.113	.117	.120	.123	.125	.127	.129	.130
14,000	.031	.055	.075	.090	.102	.111	.119	.125	.130	.134	.138	.141	.144	.146	.148
16,000	.031	.057	.078	.094	.108	.119	.128	.135	.142	.147	.152	.156	.159	.162	.165
18,000	.031	.058	.080	.098	.113	.126	.136	.145	.153	.159	.165	.169	.173	.177	.180
20,000	.032	.059	.082	.102	.118	.132	.144	.154	.162	.170	.176	.182	.187	.191	.195
25,000	.032	.060	.086	.108	.126	.143	.158	.170	.182	.191	.200	.208	.215	.221	.226
30,000	.032	.062	.088	.112	.133	.152	.169	.184	.198	.210	.221	.231	.239	.247	.255

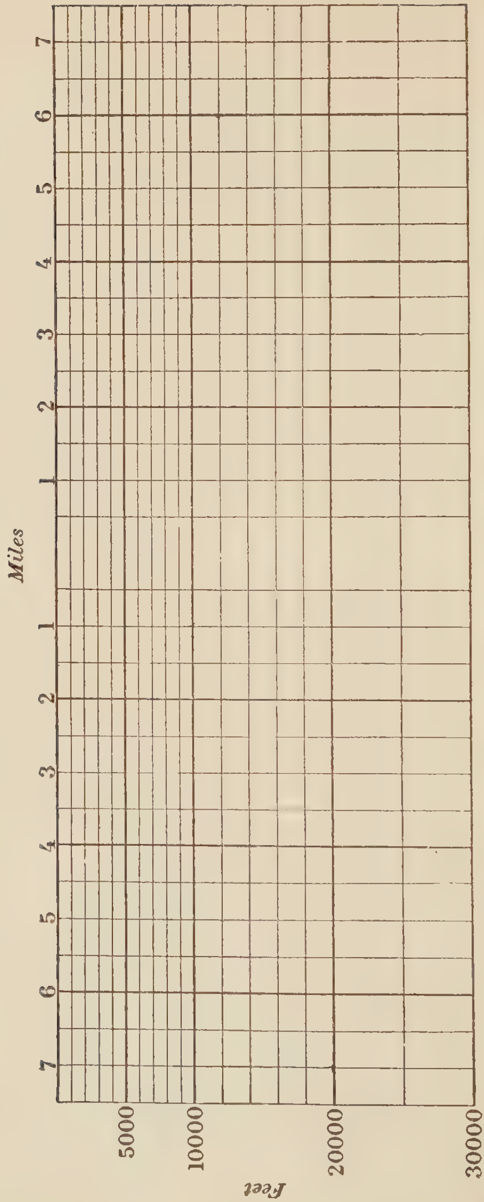


FIG. 11.—This diagram is used in connection with the above table in the computation of the effect on gravity of volumes of matter having densities varying from the normal.

the attraction for a mass of greater density, say 2.65, simply multiply the tabular value by this number. If the effect in any volume of an excess or deficiency in density is desired, multiply the excess or deficiency by the tabular value for that volume. For instance, if the excess is 0.24 and the tabular value is 0.015, the attraction is +0.004 dyne. With a deficiency of density the result will be minus. Several examples of the use of the table and diagram are given below.

What is the effect of a deficiency in density of 0.45 in a cylinder 1 mile in radius, 5,000 feet in length, with the upper end 3,000 feet below the station? From the table it is found that the effect of a column 8,000 feet in length and 1 mile in radius is 0.047. Also for a column 3,000 feet in length and 1 mile in radius the effect is 0.028. The difference between the two, 0.019, multiplied by 0.45, is the effect sought. This equals 0.009 dyne.

What is the effect of a deficiency of density of 0.35 in a cylinder 10,000 feet long and 2 miles in diameter, with its top at the surface and its axis 3 miles from the station? The value sought can not be gotten directly from the table, but we can obtain it by an indirect method.

The attraction of a cylinder 4 miles in radius and 10,000 feet long, with top at the surface of the earth, is 0.099 dyne. Similarly, for a cylinder 2 miles in radius and 10,000 feet long the attrac-

tion is 0.077 dyne. The difference between the attractive effects is 0.022 dyne.

The area of the cross section of the hollow cylinder is 37.7 square miles. The area of a cir-

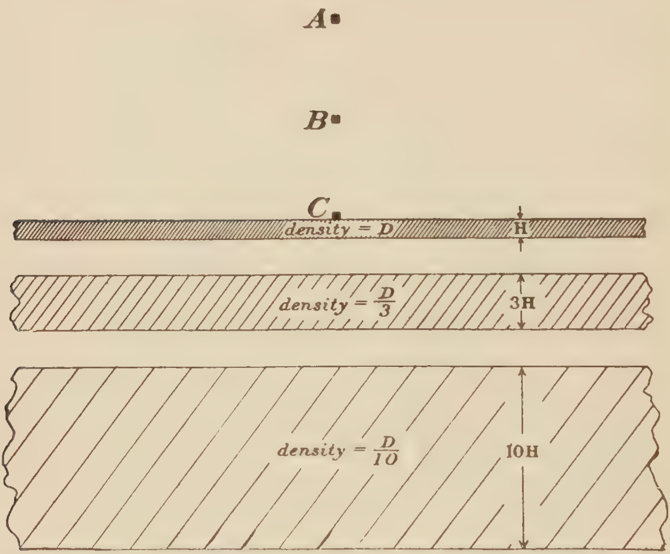


FIG. 12.—Disks of material of great horizontal extent, having different densities of material but the same mass, exert the same attraction on unit masses at the center of their upper surfaces. If the unit masses are at different distances above the surface, they are attracted equally by the disks, provided the distance is small as compared with the horizontal extent. This principle is of importance in making isostatic investigations.

cle 2 miles in diameter is 3.1 square miles. Therefore, the ratio, 3.1 divided by 37.7, multiplied by 0.022 dyne, the attraction of the hollow cylinder, will give the attraction of the cylinder 2 miles in radius, which equals 0.0018 dyne.

Now, multiply this by 0.35, the deficiency of density, and the answer is 0.0006 dyne.

Let the conditions be as in the above problem except that the top of the cylinder is 5,000 feet below the surface. First, we find the value of a cylinder 4 miles in radius and 15,000 feet in length with its top at the surface. The value is 0.130 dyne. From this subtract the effect of a cylinder 4 miles in radius and 5,000 feet in length, 0.056 dyne. The difference is 0.074 dyne. Next, take the value from the table for a cylinder 2 miles in radius and 15,000 feet in length, 0.092 dyne. From this subtract 0.050 dyne, the value for a cylinder 2 miles in radius and 5,000 feet in length. The difference is 0.042 dyne. Subtract 0.042 dyne from 0.074 dyne and we get 0.032 dyne, which is the value of the effect of a hollow cylinder with inner radius 2 miles and outer radius 4 miles, 10,000 feet in length with its top 5,000 feet below the surface. As in the previous problem, multiply the ratio of the area of the circle 2 miles in diameter to that of the cross section of the hollow cylinder, 3.1 over 37.7, by 0.032 dyne, and we have 0.0027 dyne as the attraction of the cylinder for unit density. Then multiply 0.0027 dyne by 0.35, the deficiency of density, and we get 0.0009 dyne, the value sought.

It is readily seen that from the table one can obtain the value of the attraction of masses of

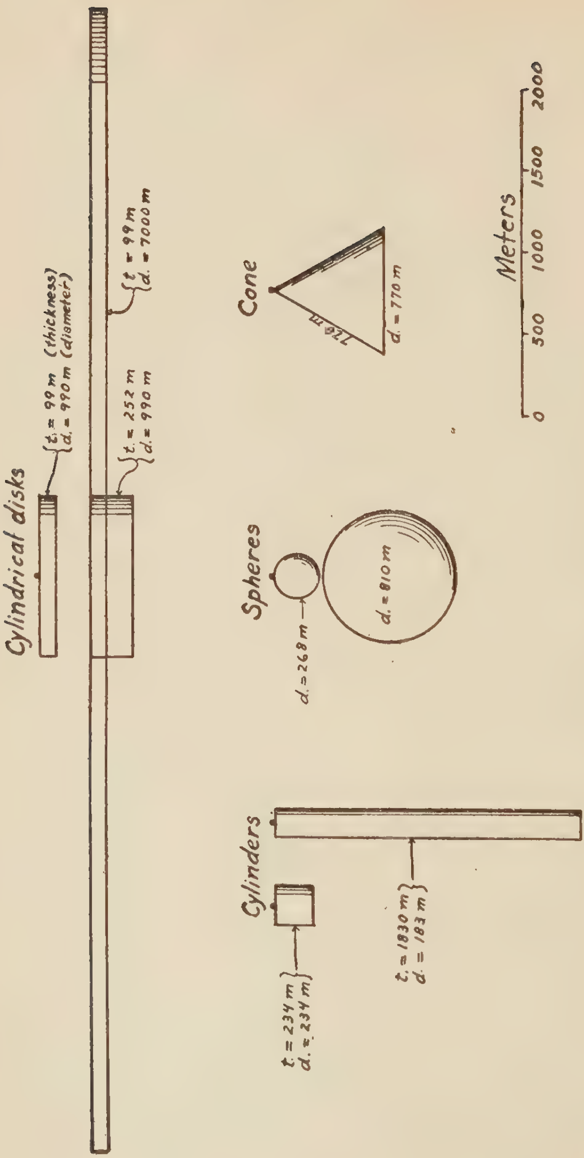


FIG. 13.—Masses of various shapes and sizes each of which will cause an attraction of 0.010 dyne on a unit mass located as shown.

various dimensions situated in different positions from the station. For a sphere or cube an equal volume of the hollow cylinder can be used with sufficient accuracy.

Should the table not be comprehensive enough it may be readily extended. The formula for the attraction in dynes of a right cylinder on a unit mass (1 gram) located outside the cylinder but on its axis is

$$2\pi K\delta\{\sqrt{c^2+h^2}-\sqrt{c^2+(h+t)^2}+t\}$$

in which K is the gravitation constant, δ is the density of the material, c is the radius of the cylinder, t is the length of the element of the cylinder, and h is the distance from the attracted mass to the nearest end of the cylinder. The value of K may be taken as $6673\ (10^{-11})$.[4]

[4] See U. S. Coast and Geodetic Survey *Special Publication No. 10*, 1912, pp. 13 and 17.

CHAPTER IV

ISOSTATIC CONDITION OF EARTH'S CRUST UNDER VARIOUS CLASSES OF TERRAIN

Relation of Gravity Anomalies to Topography

If the earth were rigid with land masses as overloads on the crust and with the deficiencies of mass in the oceans as underloads, the gravity anomalies on this theory would be the same as the attractive effect of the masses above sea-level, diminished by the negative attractive effect of the ocean deficiencies of mass.

The isostatic gravity anomalies are, on an average, only 15 per cent of what the anomalies would be if the earth were considered rigid. This is the most important fact resulting from the isostatic investigations, for it shows that the earth's crust is very nearly in complete isostatic adjustment.

In the Bouguer method of reducing gravity data no account is taken of the isostatic compensation. The average and maximum Bouguer and isostatic anomalies in the United States are given in the following table.[1]

[1] Each of five groups of stations was treated as a single station by taking the mean anomaly for the group.

	Number of stations or groups	Average without regard to sign	Average with regard to sign	Maximum
		Dyne	Dyne	Dyne
Bouguer anomalies....	296	0.048	−0.036	0.229
Isostatic anomalies....	296	.021	−0.006	.093

Of the 296 anomalies 208 of the Bouguer are negative and 87 are positive, but of the isostatic 168 are negative and 126 positive. The average Bouguer anomaly with regard to sign is — 0.036, but the isostatic is only — 0.006. This is strong evidence in favor of the theory of isostasy.

A very severe test of the theory of isostasy is given by the relation of the anomalies to the elevations of the stations. This test shows whether the anomalies are different from the various topographic conditions. In the following table are given the average Bouguer and isostatic anomalies in the United States for various elevations:

Elevation of stations in in meters	Number of stations or groups	Average Bouguer anomalies		Average isostatic anomalies	
		Without regard to sign	With regard to sign	Without regard to sign	With regard to sign
		Dyne	Dyne	Dyne	Dyne
0 to 400	213	0.027	−0.010	0.022	−0.010
401 to 800	32	.039	− .037	.018	+ .011
801 to 1,200	16	.104	− .104	.022	− .004
1,201 to 1,600	15	.128	− .128	.022	+ .010
Over 1,600	20	.184	− .184	.014	+ .003

We find very nearly the same value for the average isostatic anomalies for the five groups of elevations. On the other hand, the Bouguer anomalies have a very definite relation in size and sign to the elevation. This test is strongly in favor of the isostatic theory.

Effect of Topography Alone on Values of Gravity

There are 219 gravity stations of the United States for which values for the effect of topography of the entire earth are available. The effect on the gravity value on Pike's Peak is +0.273 dyne, the maximum positive effect. The maximum negative effect is —0.178 dyne on the station at Compton, California. Of the 219 stations, 63 have topographic effects greater than 0.150 dyne. Nearly all these large effects are for stations near the coasts. For the coast stations, the effect of water areas is greater than that of land, both on account of the average depth of the water being greater than the average elevation of the land and on account of the greater area of water. For the United States the vertical component of the negative attraction of the deficiency of the water is generally greater than the vertical component of the positive attraction of the land masses. For stations in the interior of the United States the positive effects of topog-

raphy are large, although for many of them the negative effect of the distant water areas offsets the positive effect of the land of North America—the nearby topography.

The topographic effect for only 35 of the stations is less than 0.060 dyne and there are only 58 with effects less than 0.100 dyne. The average topographic effect is 0.119 dyne.

One should keep in mind the very large topographic effects when studying the isostatic anomalies. There are only 15 of the 219 stations under consideration for which the isostatic anomaly is more than 0.040 dyne, and only one anomaly greater than 0.060 dyne. Most of the stations have isostatic anomalies less than 0.020 dyne. Due to great distance from a station of much of the topography of the earth the effect of the topography is almost balanced by its compensation, but if the compensation did not exist the effect of the topography would apply with full force.

Even though no account were taken of the combined effect of the topography and compensation, the values of gravity would be in fair accord, except those for high mountain stations. Only 14 of the 219 stations considered would then have anomalies greater than 0.060 dyne, while for 110 of them the anomaly would be less than 0.020 dyne.

If there were no compensation the values of

gravity would be greater or less than the observed values we now have by amounts equal to the compensation effects. The new values would differ from those now observed by about 0.100 dyne on an average.

The very small range in the isostatic anomalies and the many values close to zero are strong evidence that the topography of the world is isostatically compensated.

Relations of Isostatic Anomalies to Areas of Erosion and Sedimentation

There seems to be no relation between the size and sign of the isostatic gravity anomalies and areas of erosion. There may, of course, be areas of erosion in which gravity anomalies tend to be of one sign, but in such areas the anomalies are comparatively small and there is no general relation whatever that can be discovered.

On the other hand, there is a decided relation between the areas of recent deposition and the gravity anomalies, and in this group of areas is included all of the Cenozoic formation. For some years it was believed that there was a definite relation between the isostatic gravity anomalies and the margins of continents due, in some way, to conditions existing along the coast that did not obtain in the interior. It was later found

that a very simple explanation could be made of these coastal anomalies, namely, that they are due to the material along the margins of the continents which is mostly of recent formation with density from 10 to 20 per cent less than normal. This light material, nearly all below sea-level and immediately below the gravity stations, has an attractive force which is less than that of material of normal density. This explanation was advanced by the writer in U. S. Coast and Geodetic Survey *Special Publication No. 40* and it has been accepted by other geodesists, notably Col. Sir Sidney Burrard, former superintendent of the Trigonometrical Survey of India.

In a publication [2] by Colonel Burrard, entitled "Investigations of Isostasy in Himalayan and Neighbouring Regions," he gave the results of certain computations made to show the effect of a volume of light material close to a gravity station and to show what amount of sedimentary material would be required in the vicinity of gravity stations on the Indo-Gangetic plain to account for the deficient force of gravity at nearly all the stations on that plain. As a result of his investigations Colonel Burrard concluded that the prism under the Indo-Gangetic plain is probably in isostatic equilibrium, and that the

[2] *Professional Paper No. 17,* Trigonometrical Survey of India.

abnormally small values of gravity are due almost entirely to the presence of the Cenozoic material close to the surface.

We may safely conclude that the rather decided relation between the areas of deposition and the gravity anomalies can be explained by the presence of lighter material, and that the negative gravity anomalies on the Cenozoic formation are not indications of departures from the isostatic condition.

Isostatic Equilibrium of Delta Areas

The first part of a series of papers by Joseph Barrell, entitled "The strength of the earth's crust," in the *Journal of Geology,* Vol. XXII, 1914, deals with geological tests of the limits of strength of the outer portion of the earth's material. In the introduction Barrell states:

> The capacity of the outer crust to resist vertical stresses is an important field in the theory of dynamical and structural geology. On the one hand, it is known that the larger segments, those of continental and oceanic proportions, rest to a large degree in isostatic equilibrium, the crust of the continental areas being lighter than that of the oceanic areas in proportion to the regional elevation. On the other hand, the minor features, those which enter into the composition of the landscape, are known to have been sculptured by external forces and are to be explained, therefore, as sustained by reason of the rigidity of the crust.
>
> Between these two extremes in magnitude of terres-

> trial relief lie mountain ranges, plateaus, and basins, made in part by tangential forces modified by erosion and sedimentation. To what extent can these constructional and destructional forces work in opposition to those other forces which by producing vertical movement make for isostatic equilibrium?

Barrell discusses the evidence used by the geologists and the isostasists in arriving at their conclusions in regard to the strength of the earth's crust and its ability to carry extra loads.

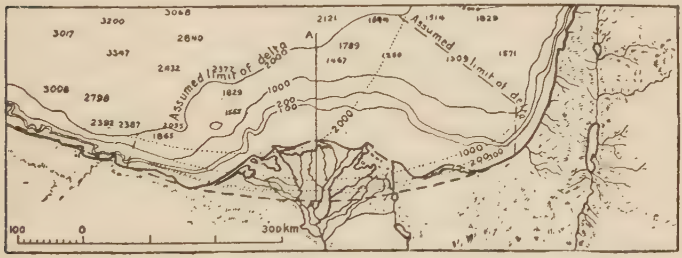


FIG. 14.—Delta of the Nile. Depths of the water are in meters. From Andree's Allgemeiner Handatlas, Vierte Auflage.

He lays particular stress on the presence of great volumes of sedimentary material at the mouths of large rivers as evidence of the strength of the earth's crust. He shows that the best two of the existing deltas for making the test of the strength of the earth's crust are those of the Nile and the Niger.

Barrell's Figure 1 (Fig. 14 in this volume) shows clearly that there has been a filling up of space at the mouth of the Nile which was once occupied by water. Similarly, Barrell's Figure

3 (our Fig. 16) indicates a filling in by deposits at the mouth of the Niger. Figures 15 and 17 copied from Barrell give vertical sections through the deltas of the Nile and the Niger, respectively.

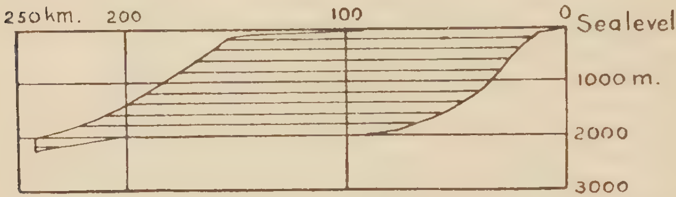


FIG. 15.—Profile of the delta of the Nile. Depths in meters. After Barrell.

Barrell computes from these cross sections and the areas shown on the charts the load added to the earth's crust in the form of sediment. In the case of the Nile the volume is computed as 89,000 cubic kilometers (21,300 cubic miles) which, after accounting for the weight of the water that originally occupied the space, is equivalent to 50,000 cubic kilometers (12,000 cubic miles) of rock on the land.

In the case of the Niger delta the volume of sediments is 217,000 cubic kilometers (52,000 cubic miles) which, after allowing for the water displaced, is equivalent to 120,000 cubic kilometers (29,000 cubic miles) of rock on the land.

After discussing the geology of the coasts of Africa and the probability (in his estimation) that the deltas under consideration are extra

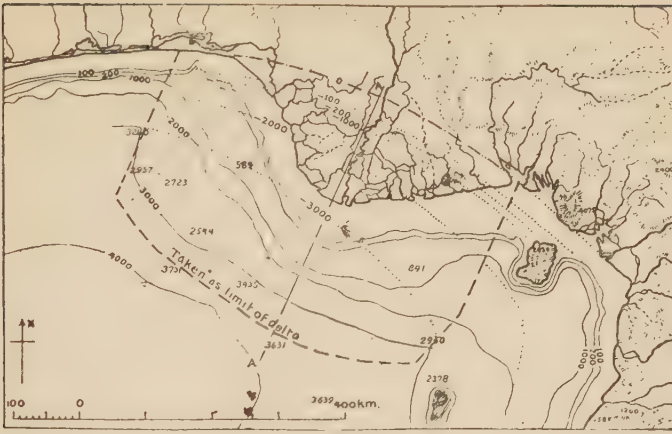


FIG. 16.—Delta of the Niger. Depths in meters. From Andree's Allgemeiner Handatlas, Vierte Auflage.

loads on the earth's crust, Barrell concludes his Chapter I with the following words:

> These deltas point toward a measure of crustal rigidity capable of sustaining to a large degree the downward strains due to the piling up and overthrusting of mountains built by tangential forces or those resulting from the load of sediments in areas of deposition or those upward strains produced by the erosion of the plateaus previously uplifted toward isostatic equilibrium. A final conclusion must, however, await a further discussion in the later parts.

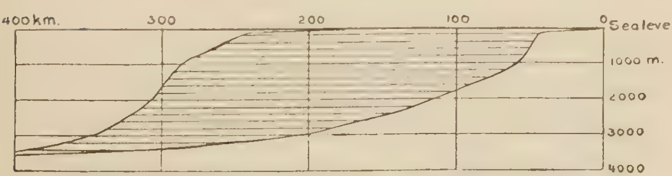


FIG. 17.—Profile of the delta of the Niger. Depths in meters. After Barrell.

In the remainder of Barrell's series of papers he deals with many phases of structural and dynamic geology and the theory of isostasy, but he does not modify the conclusions quoted above that the earth's crust is able to carry without yielding the mass represented by a large delta. Barrell may have erred in arriving at his conclusion that the earth is able to withstand the load of a mountain mass if it is able to hold up a river delta, but was he not also wrong in his conclusions regarding river deltas?

The maximum depth of the sediments in the delta of the Niger down to the former ocean bottom level is about 3,000 meters (approximately 10,000 feet). The density of this material is probably not more than 2.50. The density of the sea water which occupied the space now occupied by the sediments was slightly over 1. Therefore, we may assume that the weight of the water displaced corresponds to 40 per cent of the material taking its place, and that the other 60 per cent is an extra load. Therefore, according to Barrell, there is an overload on the earth's crust amounting to about 6,000 feet of deposits.

We can explain the presence of this 6,000 feet of added material on the principle of isostasy if we assume that much more material has been deposited at the mouth of the Niger than the 10,000 feet. We have abundant evidence that

tens of thousands of feet of sediments have been deposited in some localities, and why might there not be more than the 10,000 feet in the Niger delta?

A sinking of the base of the sediments occurs in most areas of sedimentation. This certainly occurred during the sedimentation of the areas occupied by the Appalachian, Himalayan, and other mountain systems. The sinking of the base is due mostly to the isostatic adjustment of the prism which is undergoing sedimentation.

The average density of the material of the upper sub-crustal material may be assumed to be approximately 3.15. The sedimentary material deposited by the Niger probably has a density of about 2.50. Therefore, the density of the sub-crustal material is 0.65, or 25 per cent greater than the density of the sediments. Assume that as the sediments are deposited isostatic adjustment takes place. The delta of the Niger would require a total depth of sediments, below the original position of the base, of 23,000 feet to bring the surface to the top of the water. This, with the 10,000 feet above the base, makes a total depth of the deposits of 33,000 feet. This is not believed to be an excessive depth. In India in the Indo-Gangetic plain the recent sediments are believed to be somewhat more than 40,000 feet in certain parts of the area. (See page 190 for method used in deriving these values.)

With regard to the Nile Delta, Barrell figures that there is a maximum depth of the deposits of approximately 7,000 feet. By the method of computation used above for the Niger Delta we find that the amount of water displaced by the sediments is equivalent to the weight 2,800 feet of the sediments. This leaves 4,200 feet of sediments as an excess load above the sedimentary base on Barrell's theory that the sediments are an overload.

On the theory that the base of the sediments sinks, due to the isostatic adjustment, it would be necessary to lower the base of sediments about 16,000 feet in order to give the 4,200 feet of added material in the space once occupied by the water. This, with the 7,000 feet above the base, makes a total depth of the deposits of 23,000 feet. This is not large in comparison with the depth of sediments in many places of the earth. The above reasoning is justified if the materials deposited in the form of deltas at the mouths of rivers and in the water just beyond the exposed deltas are found to be in isostatic equilibrium.

We are fortunate in having a number of gravity stations on or near the Mississippi River Delta. There are eight of these stations. (See Fig. 18.) Although the mass of the Mississippi River Delta does not show on a hydrographic chart as distinctly as do those of the Nile and

Niger, yet the river has carried material quite far out into the Gulf of Mexico, and the depth of the deposits must be considerable.

If the prism of the isostatic shell under the delta was in equilibrium before deposition began, then certainly the added material is an extra load unless some subsidence of the block has taken place. On the assumption that the delta

FIG. 18.—Gravity stations and anomalies on Mississippi River Delta. *See* legend under Fig. 21.

material is an extra load we should find positive anomalies at the gravity stations on the delta, the sizes of the anomalies being in proportion to the depth of the delta material.

Instead of finding decided positive anomalies at the eight stations on or near the delta, we find

that only four of the stations have positive anomalies of 0.012, 0.014, 0.019 and 0.002 dyne. All of these positive anomalies are smaller than the average anomaly without regard to sign for the 304 gravity stations of the United States. The other four delta stations have negative anomalies of 0.018, 0.026, 0.030 and 0.032 dyne. Three of these anomalies are larger than the average for all in the United States. The average of the eight anomalies with regard to sign is —0.007. Surely, if the delta is an extra load the pendulum observations would not give an average negative anomaly at these delta stations.

It is believed that the positive anomalies on the delta at the three stations near the mouth of the river may be due to local accumulation of material which has not yet been isostatically balanced. On the other hand, the presence of extra light material close to the station is the probable cause of the negative anomalies, and the prisms under these negative stations are probably in isostatic equilibrium. That the anomalies are due to local causes which are located near the surface is indicated by the difference in the anomalies at stations 279 and 280 which are at the mouths of the river. The difference in these anomalies is 0.037 dyne and the distance between the stations is only about 12 miles. It is certain that if the cause of either of the two anomalies in question were deep seated in the earth's crust

the effect on the two stations would be almost the same.

It is rather difficult to analyze the gravity anomalies on the Mississippi Delta in such a way as to give a logical explanation of the size and sign of each of them. It is much safer to use the whole group of stations as a single unit in drawing conclusions. Since the average anomaly of the whole group is —0.007 dyne, we are evidently justified in concluding that the prism of the isostatic shell directly under the Delta of the Mississippi is very nearly in isostatic equilibrium and that the delta material has been compensated for by a movement of material from the base of the prism.

It is unfortunate that there are no gravity stations on such deltas as the Nile and the Niger to test the degree of isostatic equilibrium which exists in the earth's crust under them. This matter is of such great interest it is hoped gravity stations will be established on these deltas in the not distant future.

Isostasy in Glacial Areas

A recent book covering researches by Fridtjof Nansen [3] leads to the conclusion that the earth's crust yields to the loading and unloading by ice.

[3] "The Strandflat and Isostasy," I Kommission Hos Jacob Dybwad, Kristiania, 1922.

His views are summarized in the following excerpts from his book:

> The fact, proved by the strandflat and by the raised shore lines, that the coast of Norway has been depressed during the last glacial period and has again in post glacial time risen to a level slightly higher than the level it had before the subsidence, while the upheaval of the land is not yet completed in the central and Baltic regions of the depressed area, which after the retreat of the ice was covered by a thick layer of sea, seems to me to form convincing evidence of the correctness of the theory that it was the load of the ice which caused the depression of the crust and the unloading which caused its upheaval. I do not think that serious objections can be any longer raised against this theory.
>
> It seems to me that the more one studies the whole process of the late-glacial and postglacial subsidence and upheaval of Fenno-Scandia, and the related crustal movements in the surrounding regions, in all their details, the more one must be convinced that these movements are isostatic. One will find that the theory of isostasy gives a simple and natural explanation of almost all phenomena and even of many details which may seem startling at the first glance.
>
> It has also been maintained that great disturbances over extensive areas are necessary to start the crustal movements for adjustment of isostasy, and such movements will occur, as a rule, only during periods of special mobility of the earth's crust and within certain specially mobile regions. As far as I can judge, the late-glacial and postglacial vertical movements of Fenno-Scandia and surrounding regions, and especially the movements of the Norwegian coast and the present position of its strandflat, conclusively disprove the correctness of views such as these. They indicate that the earth's crust in the course of time approaches its level of perfect isostatic equilibrium much more closely than

even the most extreme advocates (like Hayford) of perfect isostasy have considered to be possible.

We may, therefore, infer that the earth's crust is on the whole very responsive to disturbances of its equilibrium and has a great ability to reestablish it. After a sufficient time it will attain its level of isostasy at least within some few meters.

It is a general tendency of the lithosphere to readjust its isostasy after disturbances and in the course of time to approach its average level of isostatic equilibrium within some few meters at least. The isostatic movements of the lithosphere are not limited to especially mobile regions nor to periods of special crustal mobility.

While Nansen drew his conclusions from physiographic evidence, his deductions and conclusions are in general accord with those arrived at by the geodesist who has used geodetic data.

CHAPTER V

SOME GEODETIC AND GEOPHYSICAL DEDUCTIONS FROM THE PROOF OF ISOSTASY

Depth of Isostatic Compensation

THE theory of isostasy postulates a depth within which the compensation takes place. If a state of isostatic equilibrium exists, then there must be a limit to the outer materials of the earth which are in a state of stress due to the unequal elevations of the earth's surface.

Henry S. Washington has made a distinction between the "depth of compensation" as derived from geodetic data and the depth at which loads on equal areas are the same. The latter he calls the "isopiestic depth." The two depths are not necessarily the same unless we should define the "depth of compensation" as that one to which the deepest compensation extends.

It is probable that the compensation in some prisms of the earth's crust extends to a greater depth than in others. It is impossible to determine the depth of compensation for each topographic feature of limited extent, as the deflections of the vertical and the gravity anomalies

are undoubtedly due, in part, to other causes than the depth to which the compensation extends. Some of these other causes are: The way in which the compensation is distributed horizontally with respect to the feature; the way the compensation is distributed vertically, whether uniformly or irregularly; the deviations from normal densities of the materials within a few miles of the surface; the degree to which the region may deviate from the perfect isostatic state; deviations of the densities of the material of the topographic feature from that used in the reductions; and, lastly, though negligible, the errors of the geodetic data. It may be readily seen that this array of causes of uncertainty makes the depth of compensation derived for a small area of doubtful value.

The depth of compensation resulting from investigations by the U. S. Coast and Geodetic Survey is based upon a consideration of the deflection stations and the gravity stations over extensive areas. An average value has thus been derived for each class of geodetic data.

In his second report on the figure of the earth and isostasy[1] Hayford used all deflection stations available at the time in the United States. His value of the depth of compensation was 122.2 kilometers.

[1] Supplementary investigation in 1909 of the figure of the earth and isostasy, 1910.

The writer derived two values for the depth of compensation by using, first, all the gravity stations in the United States, and, second, only those in mountainous regions. The first depth is 60 kilometers and the second 95 kilometers. Hayford also obtained a depth of 97 kilometers from deflection stations in mountainous regions, but he did not consider this value as reliable as the larger one of 122.2 kilometers.

As the depth of compensation derived from mountain gravity stations was 95 kilometers and Hayford's corresponding depth was 97 kilometers, the writer has adopted the mean of 96 kilometers as the most probable depth.[2]

Why, it may be asked, should a value for the depth of compensation derived from a small amount of data be considered more reliable than from a much greater amount? A careful consideration of the conditions mentioned above will show why the value derived from stations in regions of considerable elevation is more reliable.

Aside from the local causes of deflection and gravity anomalies enumerated above there are the following causes having a general or regional effect: (1) Errors in the assumed figure of the earth for deflection anomalies and in the shape of the earth for the gravity anomalies; (2) error

[2] See U. S. Coast and Geodetic Survey Special Publication No. 40, p. 133.

in the value of gravity at the equator as used in the computations; and (3) regional deviations from the condition of perfect equilibrium.

The effect of each of the first two general or regional causes of deflection and gravity anoma-

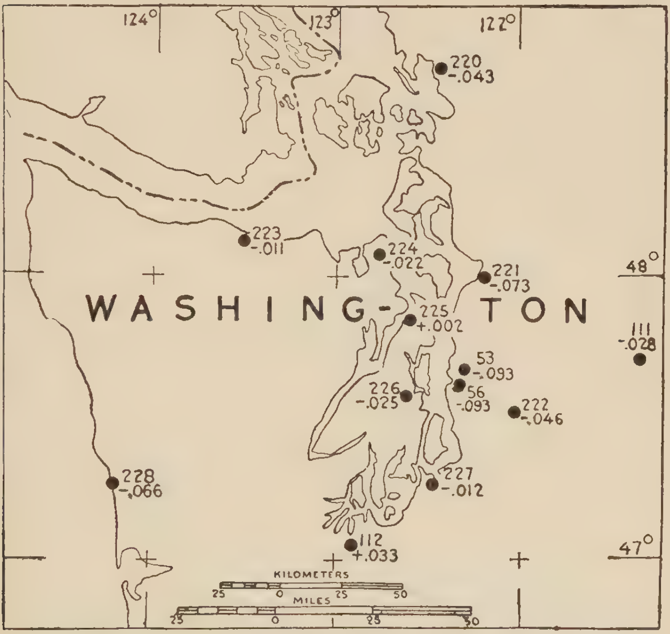


FIG. 19.—Gravity stations and anomalies near Seattle, Washington. *See* legend under Fig. 21.

lies can be eliminated. The effect of the third general cause and that of each of the numerous local causes are present in the remaining anomalies which are used in deriving the depth of compensation.

Let us consider some of the large gravity anomalies. At Seattle (see Fig. 19) the anomaly is —0.093 dyne, while the elevation of the station is only 190 feet. At a gravity station just 20 miles west of Seattle the anomaly is —0.025 dyne. At a station about 25 miles northwest of Seattle the anomaly is +0.002 dyne. The great

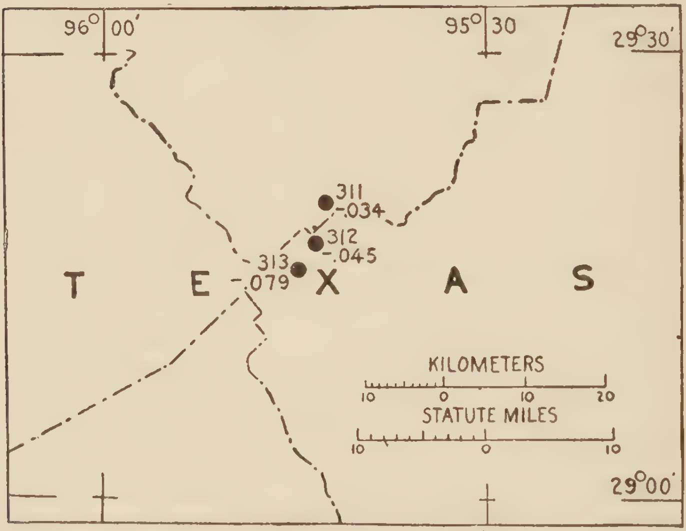


FIG. 20.—Gravity stations and anomalies near Damon Mound, Texas. *See* legend under illustrations No. 21.

difference in these anomalies is certainly due to local causes close to the surface and not to an erroneous distribution of the compensation. There is practically no topography to be compensated.

There are two gravity stations on or near

Damon Mound, Tex. (Nos. 311 and 313), which are only 7 miles apart, and their anomalies differ by 0.045 dyne. (See Fig. 20.) The elevation of these stations is less than 70 feet, and they are on a coastal plain. It is certain that here the cause of the large difference in the anomalies is local and near the surface.

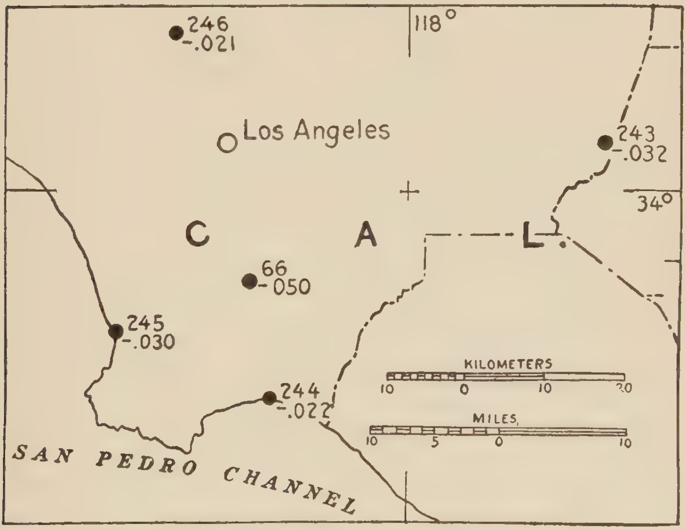


FIG. 21.—Gravity stations, with anomalies in dynes, near Compton, California. The numbers correspond to those used for the various stations in special publications dealing with gravity measurements by the U. S. Coast and Geodetic Survey.

The anomaly at Compton, Calif., is —0.050 dyne, while at Long Beach, only 8 miles distant, the anomaly is —0.022 dyne. (See Fig. 21.) The difference is 0.028 dyne. Here, again, the cause of the anomalies is local and high in the crust,

for the elevations of the stations are less than 70 feet, and no distribution of the compensation of so small an amount of topography close to the stations could affect the anomalies materially. Many other cases could be cited, and we must consider the evidence given under the heading "The relation of gravity anomalies to local structure" pages 164 to 172. It is shown there that the abnormally light material of the Cenozoic formations is the cause of at least a part of the anomalies at gravity stations on that formation, for the elevations of those stations are all small. It is impossible to greatly reduce the anomalies at the Cenozoic stations by using a different depth of compensation.

Now, let us consider the gravity stations at high elevations. Here there is a great amount of topography with a corresponding amount of compensation. Even though a part of an anomaly may be due to the local causes near the surface, a change in the depth of compensation will have a decided effect on the size and sign of the anomaly. For instance, the anomalies at Pikes Peak for no compensation, and for depths of 42.6, 85.3, 127.9, and 184.6 kilometers are, respectively, —0.204, +0.057, +0.032, +0.019, and +0.006 dyne. For the Seattle station the anomaly for no compensation is —0.111 dyne, while it is —0.093 dyne for 113 kilometers. The Pikes Peak

anomaly varies as the depth of compensation is changed, while there is practically no change in the anomaly at Seattle.

It is readily seen from the above discussion that a depth of compensation obtained from gravity data at low stations only would be inde-

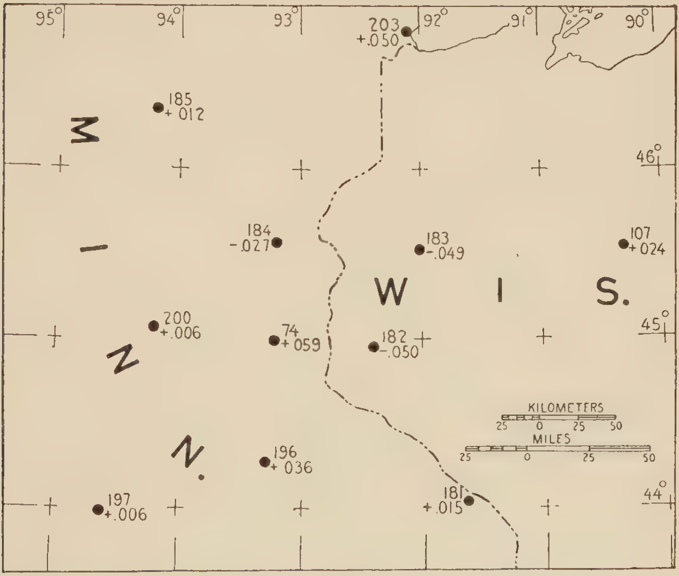


FIG. 22.—Gravity stations and anomalies in portions of Wisconsin and Minnesota. There are great changes in the anomalies for short distances, indicating that the causes of the anomalies are local and near the surface. Station No. 74 is at Minneapolis. *See* legend under illustration No. 21.

terminate, while a depth derived from a combination of low and high stations will be much in error. To obtain any depth of a high degree of

probability from the gravity data, we must use only gravity stations in high regions with irregular surfaces.

Even gravity stations on an extensive high plateau are not suitable for this purpose, for a change in the depth of compensation does not materially change the anomaly. This is due to the fact that a given mass of very great horizontal extent and of uniform density and thickness will exert the same attractive force on a particle (the gravity pendulum for instance), regardless of the distance of the particle from the surface of the material, provided this distance is much less than the horizontal dimensions of the mass. This same principle holds should the same mass be expanded to occupy a greater volume. (See Fig. 12.) The problem of obtaining a depth of compensation from only plateau stations is thus indeterminate. The more extensive the plateau and the more uniform its elevation the more indeterminate the problem. Take, for instance, the anomaly at station Wallace, Kans., No. 41 of the table on page 103, of *Special Publication No. 40*. The anomaly does not change when the depth of compensation is changed from 42.6 to 184.6 kilometers.

It is reasonable to assume that the depth of compensation which enables us to obtain the smallest gravity and deflection of the vertical anomalies in mountainous regions is the most

probable one. The depth of 96 kilometers, which is the mean of the depths derived from deflection and gravity data at mountain stations in the United States, accomplishes this and is the one believed to be the best now available.

What does the "depth of compensation" mean? On the theory that the compensation is complete, is distributed uniformly with respect to depth, and is distributed within a limited distance horizontally from the topographic features or directly under them, the derived depth of compensation is the average distance below sea level to which the compensation of the whole region considered extends. This depth may not be correct for any other extensive region, though it seems reasonable to infer that it is.

As the "depth of compensation" derived from geodetic data is the average depth to which the isostatic compensation extends, it must be true that the isopiestic depth, or the one at which pressures are equal, is somewhat greater. The difference in these depths is not known, but it probably is not great.

It should be noted that although 96 kilometers is now considered the best value for the depth of compensation, the value of 113.7 kilometers was used in computing the anomalies used in the isostatic reports of the U. S. Coast and Geodetic Survey. The 113.7 kilometer depth anomalies are used in this book unless a statement to the

contrary is made. The anomalies by the two depths differ very little and hence may be used together without introducing any appreciable error.

Size of Topographic Feature Which May Not be Compensated

We may not have local compensation of a topographic feature, for the compensation may be distributed in the isostatic shell off to the sides of the feature. This is probably the case, for it does not seem to be reasonable to have the compensation of a feature with a small base, say ten miles square, confined to a prism of the crust of such small cross-section. But we must consider whether a feature escapes compensation altogether, either directly under it or distributed within a reasonable distance around it. A test was made by the writer which furnishes information on the subject.

Forty-two gravity stations in the United States, each having an elevation greater than 1000 meters (approximately 3300 feet) were selected for the tests. The results are shown in the table on the opposite page.

If the compensation of the topography of the world is considered complete there is a maximum gravity anomaly of 0.054 dyne at these stations. There are only five stations with anomalies above 0.040 dyne, and there are 23 anomalies

Effect on gravity anomalies of ignoring compensation of topography close to stations

Number and name of station	Elevation	Isostatic anomaly	Anomalies with isostatic comp. omitted to 17.9 miles	Anomalies with isostatic comp. omitted to 36.5 miles
	Meters	Dyne	Dyne	Dyne
41. Wallace, Kans	1,005	−0.012	−0.039	−0.060
42. Colorado Springs, Colo	1,841	− .007	− .061	− .101
43. Pikes Peak, Colo	4,293	+ .021	− .049	− .092
44. Denver, Colo	1,638	− .016	− .054	− .092
45. Gunnison, Colo	2 340	+ .020	− .043	− .100
46. Grand Junction, Colo	1,398	+ .024	− .017	− .058
47. Green River, Utah	1,243	− .021	− .054	− .058
48. Pleasant Valley Junction, Utah	2,191	+ .004	− .056	− .099
49. Salt Lake City, Utah	1,322	+ .010	− .030	− .065
50. Grand Canyon, Wyo	2 386	− .002	− .063	− .110
51. Norris Geyser Basin, Wyo	2,276	+ .021	− .038	− .083
52. Lower Geyser Basin, Wyo	2,200	− .001	− .059	− .104
55. Mount Hamilton, Calif	1,282	− .003	− .017	− .020
63. El Paso, Tex	1,146	+ .007	− .023	− .047
64. Nogales, Ariz	1,181	− .050	− .079	− .096
67. Goldfield, Nev	1,716	− .013	− .056	− .087
68. Yavapai, Ariz	2,179	+ .001	− .044	− .079
70. Gallup, N. Mex	1,990	− .013	− .066	− .108
71. Las Vegas, N. Mex	1,960	+ .003	− .050	− .091
75. Lead, S. Dak	1,590	+ .052	+ .014	− .012
81. Sisson, Calif	1,048	− .010	− .043	− .068
82. Rock Springs, Wyo	1,910	+ .013	− .039	− .080
98. Alpine, Tex	1,359	+ .021	− .013	− .040
99. Farwell, Tex	1.259	− .016	− .046	− .071
102. Cloudland, Tenn	1,890	+ .004	− .021	− .035
109. Sheridan, Wyo	1,150	+ .032	.000	− .036
110. Boulder, Mont	1,493	− .015	− .061	− .092
114. Truckee, Calif	1,805	− .028	− .079	− .113
115. Winnemucca, Nev	1,311	− .009	− .041	− .071
116. Ely, Nev	1,962	− .021	− .076	− .115
117. Guernsey, Wyo	1,322	+ .036	+ .005	− .026
195. Lander, Wyo	1,635	+ .019	− .028	− .071
198. Edgemont, S. Dak	1,066	+ .054	+ .026	+ .002
202. Moorecroft, Wyo	1,295	+ .021	− .010	− .037
269. Hill City, S. Dak	1,518	+ .042	+ .002	− .025
270. Newcastle, Wyo	1,328	+ .029	− .006	− .035
271. Bridgeport, Nebr	1,114	− .008	− .037	− .061
272. Buford, Wyo	2,396	+ .046	− .011	− .054
273. Boulder, Colo	1,630	− .014	− .062	− .106
274. Lafayette, Colo	1,595	− .020	− .060	− .101
275. Brighton, Colo	1,511	− .006	− .044	− .079
276. Idaho Springs, Colo	2,303	+ .022	− .046	− .098
Mean with regard to sign	....	+0.005	−0.037	−0.072
Mean without regard to sign	....	0.019	0.040	0.072

less than 0.020 dyne. The average anomaly without regard to sign is 0.019 dyne, while the mean anomaly with regard to sign is +0.005 dyne. Of the 42 anomalies, 20 are negative and 22 positive.

If we assume that the topography of the world is compensated except that within a distance of 17.9 miles of the station, the anomalies will be as shown in the fourth column of the table. The maximum has increased from 0.054 to 0.079 dyne. There are 23 anomalies greater than 0.040 dyne and only 10 anomalies are less than 0.020 dyne. The average value of the anomalies without regard to sign has increased from 0.019 to 0.040 dyne, and the mean value with regard to sign has increased from +0.005 to —0.037 dyne.

The effect of ignoring the compensation of the topography within 36.5 miles of each of the 42 stations is indicated by the anomalies shown in the last column of the above table. The maximum anomaly has been increased to 0.115 dyne, 33 anomalies are greater than 0.040 dyne, and all anomalies except one have the negative sign. Only two anomalies are less than 0.020 dyne. The mean anomaly without regard to sign is 0.072 dyne, which is nearly four times as great as the mean anomaly without regard to sign for the isostatic anomalies. The mean anomaly with regard to sign is —0.072 dyne.

If gravity anomaly maps were constructed with the above anomalies similar to illustration No. 11 in special publication No. 40 of the U. S. C. & G. S., we should find that the high elevations of the country would correspond in location very nearly to the greatest depressions of the anomaly maps. The sign and size of these gravity anomalies show a definite and decided relation to the character of the topography.

It is probable that if a test were made, it would be shown that we could not ignore even smaller discs of topography around gravity stations. If discs of 10 miles radius and 1000 meters in thickness were considered not to be compensated there would probably be gravity anomalies larger than the isostatic anomalies, and they would bear some relation in size to the elevation of the gravity stations.

We seem to be entirely justified in concluding from the evidence furnished by the tests at the 42 gravity stations under discussion, that a topographic feature equivalent to a disc 36.5 miles in radius, and 1000 meters in thickness is compensated, and that a disc of the same thickness but only 17.9 miles radius is compensated to a large degree. This conclusion is of the greatest importance in the consideration of the strength of the earth's crust in connection with its ability to support mountain masses and deltas. If such small

masses as we have considered are in equilibrium we are forced to believe masses vastly larger are in a like condition.

The extent to which topography is compensated regionally and the magnitude of the topographic feature which does not escape compensation are matters of geological and geophysical importance, and it is hoped that further tests in new areas may throw additional light on them. The knowledge gained will be of value in the search for basic principles involved in the processes which cause changes in elevation and geographic position of surface material.

Effect of Isostasy on Geoid Surface

The effect of a mountain mass in tilting the geoid or water surface is greatly lessened by the isostatic equilibrium of the earth's crust. As prisms of the earth's crust of equal cross section have very nearly the same mass, the density of the material of a prism under a mountain mass will be less than normal. The deficiency of matter under a mountain area tends to nullify the effect of the mountain mass on the tilt of the geoid surface. Close by, the mountain's effect greatly predominates, but at a distance of about 140 miles the effect of the compensation will almost offset that of the mountain. At this distance the effect of the

mountain is reduced 90 per cent. This is a very important point, and it makes necessary a revision of some old estimates of the extent to which continents, with their high land, tilt up the geoid surface.

It has been held that the geoid must be much below the spheroid out in the oceans, but this probably is not true. At a short distance from the coast the effect of the land masses will be offset by the isostatic compensation, and only the irregular configuration of the ocean bottom will vary the relative positions of the geoid and spheroid surfaces.

The effect of the continental shelf may be large, but, as in the case of land masses above sea level, it will be offset by the deficiency of density in the material of the prism under the shelf, as compared with the density of the material of the crust under the deeper water.

From a consideration of the evidence, we may conclude that the deviation of the geoid from the spheroid is probably not more than 100 meters over a great ocean "deep," and that the area affected by such a deviation is quite limited in extent. Over land areas the deviation may be as much as 100 meters under some of the great mountain systems. It will be seen that, as compared with the smooth mathematical surface of the spheroid (the mean surface), the geoid has bumps and hollows of moderate sizes. If there

were no isostatic equilibrium in the earth's crust, the bumps and hollows on the geoid might be from 30 to 40 times greater. Considering the insignificant size of the deviations of the geoid from the spheroid we can readily understand that such deviations are not factors in dynamic and structural geology.

Effect of Reduction for Isostatic Compensation on Derived Size of Spheroid

The computed spheroid, which approximates the mean sea-level surface of the earth, depends on the astronomic and geodetic observations at what are called deflection stations. The plumb line is always at right angles to the geoid surface, and therefore a deflection of the vertical is a measure of the rate at which the geoid surface departs from the mean surface or spheroid.

Let us start at the Atlantic coast in the United States at approximately 39° latitude and work westward. If we assume that the spheroid and geoid coincide at this coast, then, under the Appalachian mountains, the geoid will be above the spheroid. This is due to the fact that the Appalachian mass attracts the plumb line and causes the geoid surface to incline upward towards the mountain. Beyond the Appalachian system the geoid will tend to approach the spheroid surface because the topographic attrac-

tion is greater to the eastward than to the westward. The two surfaces will probably come nearest to each other under the plains of the Mississippi River. West of that river the resultant topographic attraction is toward the westward and the geoid will necessarily be gradually raised above the spheroid. This raising of the geoid will increase until the Rocky Mountains are reached, where it will be a maximum. Then there will be a lessening of the distance between the surfaces just to the westward of the Rockies, and through the western part of the country this distance will increase and decrease as the mountain masses are approached and passed. It is probable that the geoid surface at the Pacific coast will still be somewhat above the spheroid.

If corrections are applied to the astronomic observations for the effect of topography and isostatic compensation, the corrected direction of the vertical will be very nearly normal to the mean surface of the earth. In consequence of this method of computation the humps or ridges of the geoid would be smoothed out, and the computed spheroidal surface would be a mean of this smoothed-out geoid, rather than of the actual one. The final outcome of this process would be to make the smoothed-out geoid surface for the United States a few meters, probably not over 10 or 20, closer to the center of the

earth than the average distance of the actual geoid surface. We are considering land areas only, for it is only on these that we have geodetic data from which to compute the dimensions of the spheroid.

The only way to derive from triangulation and astronomic observations the mathematical surface or spheroid for the whole geoid would be to have connected triangulation over all the earth. This is not possible, because the great land areas are separated by large bodies of water across which geodetic measurements can not be made. It is very probable that the process of eliminating the local deviations of the geoid caused by the attraction of the topography and compensation for the area of the United States has enabled us to obtain a spheroid which represents the mean surface of the earth very much closer than if we attempted to compute the mean spheroid from the actual uncorrected geoidal surface.

It is worthy of note that the Hayford spheroids, derived from United States data only, have dimensions which are greater than the most reliable of the previously derived spheroids. In the derivation of the other spheroids isostatic compensation was not considered, but it was by Hayford. If in an area used in deriving a spheroid the central portions have much higher elevations than the margins, and if the effect of

topography and isostatic compensation is not considered, the dimensions of the spheroid will be less than when the area has its greater elevations near the margins.

It is believed that, if the isostatic method were applied in the computation of the spheroid in each of a number of large separated areas, the derived spheroids would have a very close agreement. It seems equally certain that they would differ considerably if derived by the older methods.

Isostasy Under Ocean Deeps

Since great vertical movements seem to be due to changes in density in the prisms of the crust under the affected areas, it may be concluded that *ocean deeps* which occur close to lines of islands and along some continental shores have come into being from contraction of the material of the isostatic shell under them. It seems hardly possible that such deeps as exist near the Japanese and Philippine Islands have been permanent features of the ocean bottom. They are very active regions, for in or near them occur some of the greatest earthquakes. An earthquake is an indication of lack of gravitational equilibrium or activity on the part of the processes which change the density of the crustal material.

If the deeps are not permanent features they

are due to vertically acting forces. It is inconceivable that they were caused by horizontal forces; first, because no earth prism can move vertically downward as a result of pressure against its vertical faces; second, because if there were contraction of the earth's shell there would be no sinking of a prism into the nucleus of the earth to the extent of the depression of the surface of the prism under an ocean deep; and, third, because all land areas of the earth within which isostatic investigations have been made, are in approximate isostatic equilibrium, and it is reasonable to suppose that areas at least as large in horizontal extent as ocean deeps are now in isostatic equilibrium and were also in this condition before subsidence occurred.

Fortunately, a method has been devised by Dr. Vening Meinesz of the Dutch Geodetic Commission, with which to determine the intensity of gravity at sea. The observations are made on a submarine which is submerged during the observations. Dr. Meinesz has already made gravity observations in the Mediterranean Sea, across the Indian Ocean, and along the coast of Europe. A summary of his results is given on page 50.

The gravity values over the ocean when compared with values computed by the isostatic method give anomalies which are comparable in size with those obtained for land stations. The

anomalies also have both positive and negative signs, thus indicating that the crust under the sea as a whole is neither extra light nor heavy.

In addition to the gravity values obtained from observations made on submarines, there are many stations on islands in the oceans which throw some light on the isostatic condition of the surrounding crust. The isostatic anomalies at those stations have a strong positive tendency.

The surface materials for continental areas are nearly all of sedimentary origin, and while the sources of the sedimentary material were originally igneous rock, yet the average density of the sedimentary is somewhat less than that of igneous rocks. The greater portion of the materials exposed as islands and which form the pedestals or platforms on which they stand, are believed to be igneous.

In the isostatic reductions a density of 2.67 is used for land masses down to sea-level. This value is also assumed for those portions of the crust under ocean areas which extend above the deepest part of the ocean. Some density must be used in computing the effect of the deficiency of density of the ocean water, and in the absence of any better value, that for the average rock density for continental areas is adopted.

It seems probable that if the actual densities of the materials of islands and their platforms were known and used, the crust under island

gravity stations would be found to be in equilibrium.

Dr. Meinesz made a voyage during 1926 on a submarine from Holland to Java by way of the Panama Canal. He determined values of gravity over and near some of the ocean deeps. Unfortunately, the isostatic anomalies for those stations are not yet available.

The assumption is logical that isostasy exists under the sea to an extent at least equal to that under land areas. The land masses and the continental shelves are subject to rapid erosion and deposition, respectively, which disturb the isostatic balance much more than the very slow erosion and deposition which may be occurring under the oceans would disturb the crust below them. If the crust under land areas is yielding to the stress differences caused by erosion and deposition why should not the crust under the oceans yield to stress differences accumulating in it?

If the crust under oceans is in equilibrium, if this condition obtains for that portion of the crust under an ocean deep, and if the deep has been formed within geologic time, then the conclusion should be drawn that the deep is due to a contraction of the column of the isostatic shell under it. What could have caused this column to contract?

The geologic record shows that areas which

were once occupied by mountain systems are now at or below sea level, showing that a once elevated area is now an area of depression. This depression must have been caused by a contraction of the crust under the area. Are we not justified in assuming that when a land area has been greatly depressed it was once an elevated area and consequently an area of erosion?

It is shown in another part of this book that the depression of an area subject to long continued erosion may be due to the fact that the material carried into the base of the prism in the process of the isostatic adjustment will force upward the materials of the prism. They will occupy spaces which are colder than those they formerly occupied. As the geoisotherms resume their normal depths during or after the cessation of erosion, the material of the prism will have a lower temperature. This change in temperature should tend to initiate physical or chemical processes which would result in an increase in the density of the affected material. This would be in addition to the normal thermal contraction.

Are we justified in reasoning by analogy that an ocean deep was once an elevated region which previous to its depression had been subjected to a long period of erosion, during which large amounts of matter entered the lower portion of the isostatic prism under the area to maintain the

isostatic balance? If this were the case we should expect a subsequent cooling and contracting of the material of the prism as the geoisotherms receded to their former positions.

If we have a condition of isostatic equilibrium in oceanic islands then it is probable that a condition of equilibrium existed in the prisms under them before their uplift began. Is it possible that the islands occupy an area which was once an area of deposition or sedimentation, the material coming from nearby elevated region now occupied by ocean deeps?

Suppose, for instance, that the ocean deep off the Japanese Islands had once been an area of elevation and erosion, and that much of the eroded matter had been placed to the westward. After erosion had ceased we should expect the prisms under the sediments to expand and cause an increase in elevation of the surface thus creating the present islands. It may be held that they are largely volcanic, but does this materially interfere with the ideas outlined? Effusive and intrusive action must be phases of the processes working to uplift any region. An outflow of magma from rifts or faults and the creation of volcanic mountains are not in any way in conflict with the theory that an area is elevated by the expansion of the material of the crust under the area undergoing uplift.

It is probably true that no great change in the elevation of a portion of a continent occurs

except where great erosion or sedimentation has taken place. It would seem to be the case that no great change in elevation of the bottom of the oceans takes place except under similar conditions. We, therefore, should suspect that ocean areas far removed from land are more stable, and tend to undergo smaller fluctuations in elevation than those areas near land which are subjected to rapid sedimentation.

In considering the depression of a section of the ocean bottom, we must remember that the water over the area must be taken into consideration. Should the area be depressed by contraction below sea level, the water of the ocean which may then rest on the prism would push down the prism an amount sufficient to balance the mass of water above.

If the surface of the prism were depressed 30,000 feet below sea-level, and the surface were at sea-level when the subsidence began, we should expect a contraction of the material of the prism equivalent to 20,000 feet, and a sinking of the whole prism of 10,000 feet to balance the weight of the 30,000 feet of water.

Very little has been written on the subject of the relation of coral islands to isostasy. The subject is really a complicated one, for most islands on which there is coral growth now have volcanic activity, or show there has been such activity in not distant geologic time.

Coral rock is an added load to the prism of

the crust beneath, and if the mass accumulated is great the prism should be depressed to restore balance. It is shown in another part of this book that a disk of material, of surface density, 3000 feet in thickness and about 30 miles in diameter does not entirely escape isostatic compensation. A like mass, such as coral rock, added to a prism should force the prism down. The equilibrium would be restored by the movement of subcrustal material. Is it not probable that atolls are the result of the sinking of the prism below under the weight of the accumulated coral rock? The sinking of the prism would eventually submerge the central island mass if that were true.

It would seem to be probable that a prism of the crust greatly overloaded by coral rock would be subjected to temperature changes similar to those which must occur under area undergoing sedimentation. Is it possible that subsequent expansion of the prism subjected to the overload of coral expands and elevates the surface, thus exposing coral beds? Is it also possible, that this expansion, if it occurs, is the cause of volcanic activity on many oceanic islands?

Coral islands should present a fruitful field for geophysical research now that isostasy has been established. There exists a vast amount of geological data regarding them which have been collected and discussed by E. C. Andrews, H. A. Brouwer, Rollin Chamberlin, R. A. Daly,

Charles Darwin, W. M. Davis, G. A. F. Mohlengraaff, T. W. Vaughan, and many others. The research could be made more effective by the determination of values of gravity on coral islands which could be done without great difficulty.

Theoretical Gravity

Gravity Formulas of 1912 and 1917

In the gravity investigations of which *Special Publication No. 12* of the U. S. Coast and Geodetic Survey is a report, a new gravity formula was derived which appeared to agree more closely with the conditions in the United States than did the Helmert formula of 1901. The new formula is (see p. 25, Sp. Pub. No. 12):

$$\gamma_0 = 978.038\ (1 + 0.005304 \sin^2 \phi - 0.000007 \sin^2 2\phi)$$

As the second term of this formula agreed so closely with that of the Helmert formula, the Helmert value was adopted, thus making what is referred to as my 1912 formula, which is as follows:

48 .005 59

$$\gamma_0 = 978.038\ (1 + 0.005\cancel{302} \sin^2 \phi - 0.000007 \sin^2 2\phi)$$

The "isostatic anomalies" are derived from the use of this formula. It is the basis of the isostatic anomalies in *Special Publications Nos. 12, 40* and *99*.

In the gravity investigations covered by

Special Publication No. 40, a gravity formula was derived from 348 stations of the United States and other countries. It is—

$$\gamma_0 = 978.039\ (1 + 0.005294 \sin^2 \phi - 0.000007 \sin^2 2\phi)$$

This, my 1917 formula, is very nearly the same as the 1912 one. Some of the gravity anomalies for stations not in the United States considered in this book are based on the former, but the anomalies by the two differ very little and the conclusions drawn from them are essentially the same as if all the anomalies had been derived from the same formula.

The reciprocal of the flattening of the earth from the 1917 formula is 297.4, while the value from the derived 1912 formula (not the adopted one) is 298.0. The values for the Helmert 1901 and 1915 formulas are respectively 298.2 and 296.7. The value obtained by Hayford in his second investigation of the deflection of the vertical and isostasy is 297.0.

Helmert Formula of 1915

In 1915 Helmert derived the following formula:[3]

$$\gamma_0 = 978.052\ [1 + 0.005285 \sin^2 \phi - 0.000007 \sin^2 2\phi \\ + 0.000018 \cos^2\phi \cos 2(\lambda + 17^\circ)]$$

[3] Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften, No. 41 (1915), p. 676, entitled "Neue Formeln für den Verlauf der Schwerkraft im Meeresniveau beim Festlande."

in which ϕ, as usual, is the geographic latitude and λ is the longitude from Greenwich, east longitude being positive. The formula corresponds to a spheroid with three unequal axes, the shorter equatorial axis being in longitude 73° east from Greenwich and the longer, which exceeds the shorter by 230 meters, in longitude 17° west of Greenwich. The reciprocal of the mean polar flattening is 296.7±0.4. The mean value of gravity over the sphere is 979.771 dynes. The formula is based upon 410 stations in all parts of the world selected for being neither too near to the coast nor to mountainous regions and upon certain coast stations which were given reduced weight.

The coefficient of $\sin^2 2\phi$ is based on the theoretical calculations of Darwin and Wiechert.[4] It corresponds to a spheroid of revolution in hydrostatic equilibrium. This spheroid is not an exact ellipsoid of revolution, but in latitude 45° is depressed about 3 meters below a concentric ellipsoid of revolution having its equatorial and polar axes coincident in length and direction with those of the spheroid.

The coast stations were used in determining all other constants except the first one, which

[4] G. H. Darwin. "The theory of the figure of the earth carried to the second order of small quantities." Month. Not. Roy. Astr. Soc. 60 (1900), p. 82. Also "Scientific Papers," Vol. III, p. 78.

E. Wiechert. "Ueber die Massenvertheilung im Innern der Erde." Nachr. v. d. Kön. Ges. d. Wiss. zu Göttingen. Math.-phys. Kl. 1897, 221.

from coast stations alone had the special value of 978.068 dynes. The precise number of coast stations is not given. The formula, when the first coefficient is used as 978.052, represents gravity reduced by the free-air method for stations in the interior and not in mountainous regions.

This formula of Helmert is somewhat different from the U. S. Coast and Geodetic Survey formulas of 1912 and of 1917, both in the value of gravity at the equator, namely, 978.052, and in the value of the second term 0.005285. As Helmert did not apply the theory of isostasy in deriving his formula, it will not be used in this publication.

There are 134 stations in the United States, not on the coast and not in mountainous regions, treated in *Special Publication No. 40.* (See pp. 64 and 65 of that paper.) The mean free-air anomaly with regard to sign for those stations is +0.012 dyne. It is noteworthy that this is within 0.002 of being the difference between the first terms of Helmert's formula of 1915 and of the 1912 formula of the Coast and Geodetic Survey.

Helmert derived his longitude terms from stations which were not reduced for the effect of topography and compensation, nor was any account taken of the decided effect of recent sedimentary matter on the value of gravity. The writer believes that the effect of all local influences should be eliminated from the gravity

data before using them for the determination of the shape of the earth. If each coast station were affected by the same amount, then we would be justified in using uncorrected values of gravity for the derivation of the longitude terms, but an inspection of coast stations clearly indicates local disturbances. Island stations differ from main coast stations.

Proposed Form of Gravity Formula

The complete gravity formula really should be of the form

$$\gamma_0 = \gamma\,(1 + C_1 \sin^2 \phi - C_2 \sin^2 2\phi) + H + T + C_t + D,$$

where γ_0 is the value sought, γ the gravity at sea level at the equator, C_1 and C_2 are constants, ϕ the latitude of the station, H the correction for elevation of the station above sea level, T the correction for topography, C_t the correction for isostatic compensation, and D the correction for abnormal densities in the material close to the station. The last correction can not be derived with any great certainty, because the volume and shape of the extra light or heavy matter can not be accurately determined. The correction H is negative for all stations above sea level, while the corrections T, C_t, and D may be positive or negative.

A careful consideration of the literature on the subject of gravity reductions will convince

one that the gravity anomalies based upon a gravity formula which considers the sea-level surface as an ellipsoid of revolution are functions of the reduction for topography and compensation and to a certain extent of the geological formation on which the station is located. In brief, a gravity anomaly is caused, to a large extent, by something local, and probably not by the earth's figure having three unequal axes instead of two.

CHAPTER VI

SOME PHASES OF ISOSTATIC ADJUSTMENT

Re-establishment of the Isostatic Balance

Eroded material is usually transported long distances to the place or places where it is deposited. In the case of a river like the Mississippi, the distance from the source to its mouth is about 2500 miles. The material eroded by water which flows into the Mississippi is distributed along the water courses. The coarser material rests at the bases of the slopes from which eroded. The finest material is carried to the mouth of the river, some being deposited to build up the delta and the remainder going out into the Gulf of Mexico.

Ordinarily we use a very simple case to illustrate the process of isostatic adjustment. We speak of the area of erosion and the area of deposition as if they were sharply defined, with no erosion or deposition occurring in the region between them. It is of course necessary in outlining a principle to use simple illustrations, but in carrying the researches on to

greater details we must consider all the modifications of the simple illustration. (See Fig. 23.)

In the simple case we also assume that there is a movement of sub-crustal matter from the area of deposition toward the area of erosion without any large disturbance of that portion of the isostatic shell which intervenes. In the fol-

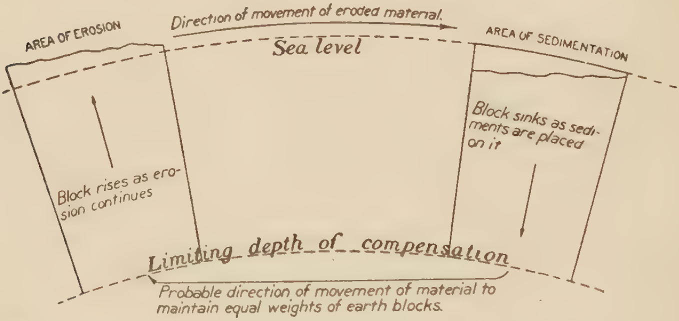


FIG. 23.—The disturbance of the gravitational balance of the earth's crust, by erosion and sedimentation, seems to be the most important factor in the processes which change the configuration of the earth's surf ce. Material is moved over the surface from high ground to water areas and to valleys by streams and rivers. The prisms of the earth's crust sink under the sediments and they rise up where erosion has lightened them. There is a sub-crustal movement of material which restores the equal weights of the blocks or prisms of the crust.

lowing discussion we shall try to throw some light on the forces and movements tending to re-establish the isostatic balance, throughout the region in which they are acting.

Let us assume that there is a definite region of limited extent which is being eroded, and that there is another region on which the eroded ma-

terial is deposited, and also that there is neither erosion nor deposition in the intervening area. Also assume that the areas of erosion and deposition are equal in extent. As erosion progresses, the prism under the erosion area becomes out of balance with the prisms surrounding it and there will be a tendency for a local adjustment to take place, restoring the equilibrium. This process should result at first in a lowering of the areas surrounding the erosion area.

Following this re-adjustment there would be a tendency for the prisms of the zone still farther away from the erosion area to re-establish equilibrium with the zone immediately surrounding the eroding area. This process would be continued until the stress differences between zones would become smaller than the resistance to yielding.

In the area within which deposition is occurring the prism below will be out of balance with the prisms surrounding it, and there will be a tendency for those prisms to come into balance with the prism under the area of deposition. There will be a tendency for the surfaces of the surrounding prisms to become elevated above their original positions. After such a local isostatic adjustment takes place, then there would be a lack of equilibrium between the prisms surrounding the area of deposition and prisms in a still more distant zone. Each zone would come

into balance with its neighboring zone until the stress differences due to lack of balance would be less than the power of resistance of the material affected.

It seems reasonable to assume that there is some local readjustment of equilibrium between the prism under an area of erosion and the surrounding portions of the isostatic shell, and a similar adjustment between a prism under an area of deposition and the surrounding region before isostatic equilibrium is perfected between the areas of erosion and deposition. When the area of deposition has come into equilibrium with the area of erosion, we should expect the regions surrounding these two areas, which had been temporarily disturbed, to regain very nearly their former status, with restoration of the original elevations of their surfaces. May not the tendency to perfect the local balance around an area of rapid erosion and deposition account for some of the minor oscillations of the elevation of the earth's surface?

We have discussed a very simple case of limited area of erosion and also a limited area on which the eroded material is deposited. No such simple case occurs in nature, for the erosion of a drainage area and the deposition of the material is a very complicated process. The extent and rate of erosion will vary with the steepness of the slopes, amount of rainfall, amount of run-

off, and the character of the material. The deposition will also vary with the slopes and the carrying capacity of the streams and rivers. Some of the material of the drainage basin will be carried into the oceans in solution and deposited at great distances from land. We can see from this that it is impossible to visualize, except in a most general way, the stress differences set up by erosion and deposition, and the movements taking place to restore the isostatic balance.

The conditions are even more complicated than those considered in the preceding paragraph, for a mountain system may form a part of several drainage areas or basins, each with its erosion and deposition, and within each a system of forces tending to restore equilibrium. It is this complicated condition which has led many to hold that the isostatic condition can obtain in only a very general or regional way. This view seemed logical and justifiable prior to the isostatic investigations, based on a vast number of geodetic observations, which have been made during the past twenty years.

The re-establishment of the isostatic balance has been discussed in a number of papers. Of especial interest are: "The Strandflat and Isostasy," by Nansen; "Oscillations of the Level in the Belts peripheral to the Pleistocene ice-caps," by Daly; and "Isostasy," by Lawson.

Zone of Horizontal Movement

One of the most important phases of isostasy from a geological standpoint is the question of the depth at which the isostatic flow or adjustment takes place. Barrell, in the "Strength of the Earth's Crust," Part VI (*Journal of Geology,* October–November, 1914, p. 681) argues in favor of a zone of weakness below the crust, which he calls the asthenosphere, in which the isostatic movement horizontally takes place. Willis agrees with Barrell that the isostatic movement horizontally takes place below the crust.[1] The writer feels that Barrell's and Willis's views that the movement is below the crust are reasonable and justifiable.

If the earth's crust were weak enough to permit isostatic adjustment to take place comparatively near the surface then the material would probably be so weak that masses of different densities would tend to flatten out and to adjust themselves in strata, each having a uniform density. The heavy material under the oceans would move under the continents and the light material of the continents would move out over the ocean floor. The heavy material under a broad plain would move under the adjacent mountain area and the material under the moun-

[1] Bailey Willis, "Discoidal Structure of the Lithosphere." *Bulletin* of the Geological Society of America, June 30, 1920, p. 251.

tains would overflow the denser material of the plains. This, as we have found from the studies of the deflections of the vertical and the gravity observations, has not taken place. We have denser material under the plains and lighter material under the mountains, and this condition tends to remain so. We must conclude that in the prism down to the lower limit of compensation the material is of sufficient viscosity to resist the stresses tending to cause the transference of material horizontally due to different densities.

There is no doubt that isostatic adjustment takes place, and therefore there must be a zone within which horizontal movement occurs. Since, for the reasons stated above, this movement could not take place within the crust, it is logical to conclude that the movement is in what Barrell terms the asthenosphere or zone of weakness. Barrell showed a diagram which would indicate that he believed the thickness of the asthenosphere to be several times the thickness of the crust. Undoubtedly, the zone of weakness may be of considerable thickness and may extend to the earth's center, but it is more reasonable to believe that the isostatic adjustment takes place within a short distance of the crust.

In order to visualize the problem, let us suppose that we have a mountain mass of a certain horizontal cross section and an adjacent plateau of the same area 3,000 feet lower than the

average elevation of the mountain. It can be readily shown that if the two prisms below these areas are in isostatic equilibrium, then at any depth below sea level but above the depth of compensation the pressure on an imaginary horizontal surface will be greater for the mountain prism than for the plateau one. At a depth of 5,000 feet below the surface of the plateau prism the pressure would be that of 5,000 feet of material, but on the same surface under the mountain the pressure would be that of 8,000 feet of material. The stress difference at the depth in question would tend to cause a movement from the mountain prism toward the plateau prism. (See Fig. 24.)

If we assume that the depth of compensation is 60 miles below the surface of the plateau prism, then at a depth of 30 miles, half way from the surface to the depth of compensation, we should expect the deficiency of density due to the isostatic compensation of the mountain prism to counterbalance 1,500 feet of the 3,000 feet at the top of that prism, and the weight on this surface at a depth of 30 miles would be greater for the mountain prism than for the plateau prism due to the remaining 1,500 feet of material. The stress difference would still be acting from the mountain toward the plateau prism. At a depth of 45 miles below the surface the stress difference would be the equivalent of the weight of

750 feet of material and would still be from the mountain toward the plateau prism. It can be seen from the above that if the isostatic compensation is uniformly distributed there will not be a zero stress difference between the mountain and the plateau prisms until the depth of com-

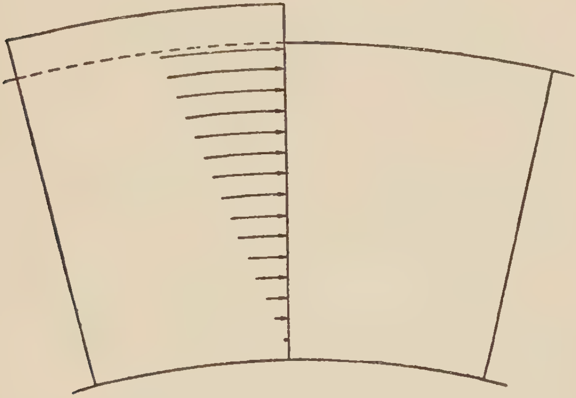


FIG. 24.—Since the earth's crust is in isostatic equilibrium for contiguous blocks of the earth's crust having different surface elevations, the stress differences are from the higher to the lower block. The stress difference is zero at the lower ends of the blocks which correspond to the lower limit of the earth's crust.

pensation is reached, approximately 60 miles below sea level.

Suppose some material is eroded from the mountain area and deposited on the plateau prism. The stress difference at the depth of compensation will then act in a direction from the plateau toward the mountain. There will be a surface somewhere above the depth of compen-

sation at which the pressure of the lightened mountain prism will exactly balance that of the plateau prism which has been increased by the weight of the eroded matter. If 100 feet of material, on an average, is eroded from the mountain prism and placed on the plateau prism, we should expect the surface at which the two will exert equal weight to be 56 miles below the surface or 4 miles above the depth of compensation. Below this surface the stress difference will be from the plateau toward the mountain, and if this stress difference is great enough to overcome the resistance of the material a movement will take place from the plateau toward the mountain tending to bring the two prisms into equilibrium again at the depth of compensation. (See Fig. 25.)

It is probable that this movement actually takes place below the depth of compensation because of the fact that the material below the depth limiting the compensation must differ from the material above in rigidity or viscosity. The fact that we have a depth of compensation implies a plastic material below it, and there is no reason why this material should not move rather than the material above, which is rigid enough to maintain its position in spite of different densities in adjacent prisms.

If the depth of compensation is above the depth of equal pressure the problem outlined

above and its solution should be slightly modified, but the general principles and conclusions would be unaltered.

Figs. Nos. 24 and 25 show the relative stress and their directions between two prisms of the crust both before and after erosion.

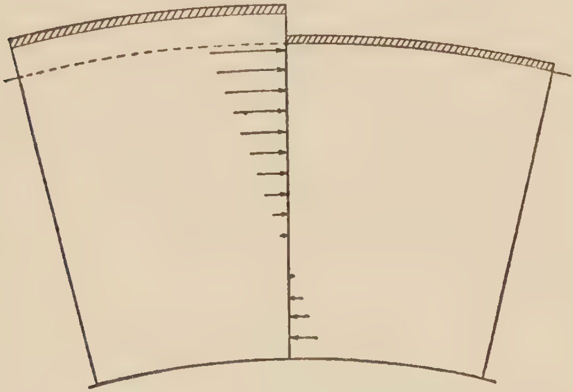


FIG. 25.—Should some material be rapidly eroded from the high block and the material be deposited on the lower one there would result a disturbance of the isostatic equilibrium. Prior to the readjustment the surface at which there would be zero stress differences between blocks would be somewhat above the lower limit of the crust. The stress differences above the point of zero stress would be from the higher block towards the lower one. Below the point of equal pressure the stress difference would be from the low block toward the high one. After the isostatic readjustment had occurred, the stress difference would be zero at the lower limit of the crust as it was before transfer of load at the surface.

MOVEMENTS OF SUBCRUSTAL MATERIAL UNDER AREAS OF EROSION AND SEDIMENTATION

If erosion and sedimentation are the primary causes of the great changes in the elevation of

the earth's surface, then it would seem to be probable that there are a number of shifts, up and down, of the margin of a continent, or of the contiguous ocean. The earth's crust sinks down under sedimentation, and a mass of material equivalent to the sediments is pushed aside from the subcrustal space just below the crust under the sediments, or it is possible that the material just under the crust goes down, and pushes aside the material surrounding it. In any event there is less subcrustal material under the sedimentary area than there was before the sediments were laid down. The subcrustal space has been occupied by the lower portion of the crust.

It is probable that there is no such thing as a *flow* of subcrustal material from below an area of sedimentation to space below an area of erosion. There is merely a pushing aside, and probably the mass of subcrustal material involved is rather large. I like to think of the movement of subcrustal material, to balance the effect of erosion and sedimentation, as similar to that of water into which is placed a block of wood or ice. There would be a pushing aside of the water to make way for the block, and the whole body of water would be affected. The lateral movement of any particular particle of water, however, would be quite small. (See Fig. 26.)

A prism of the crust may be subjected to erosion and sedimentation several times. During erosion there will be an influx of subcrustal material to crustal space to balance the material removed at the surface, and when the prism is subjected to sedimentation, crustal matter will enter subcrustal space; then in subsequent geologic periods these processes will be repeated.

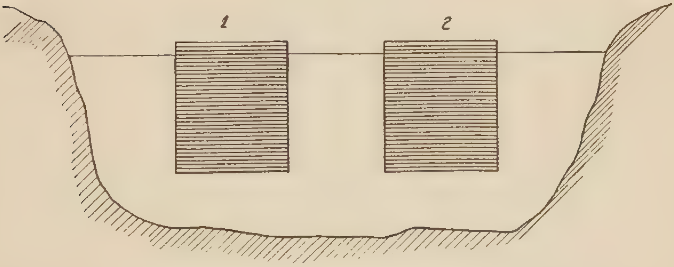


FIG. 26.—Piles of inch-boards, floating in the water, illustrate movements of crustal material due to erosion and sedimentation. Assume the density of the boards to be 0.9. Should a board be taken from the top of pile 1 and added to the top of pile 2, all the remaining boards of pile 1 would move upward 0.9 inch. The surface of pile 1 would be 0.1 inch lower than formerly. Each of the boards in pile 2 would sink down 0.9 inch, as a result of the added load, and the new surface of pipe 2 would be 0.1 inch higher than formerly. With continued shifting of boards from pile 1 to pile 2, the surface of pile 1 would be gradually lowered and that of pile 2 gradually increased. Prisms of the earth's crust react similarly to erosion and sedimentation.

Does it not seem that we may have the same material that was once pushed aside under the effects of sedimentation brought back to its former position under the influence of erosion?

Possibly there is not much migration of the subcrustal material as a result of the forces that are acting to cause the changes in the earth's surface.

The question may be asked what changes take place in the crustal material that is pushed down to subcrustal space under the weight of sediments? The answer, of course, to that question must be that we do not know, nor is there any way to obtain information in regard to it, but it would seem that this crustal material would be altered. There must be a difference between crustal and subcrustal material, otherwise we could not have a lower limit to isostatic compensation. It is the inherent difference between crustal and subcrustal materials that makes compensation possible. Crustal material pushed down a few miles into subcrustal space, should under the new pressure and heat conditions acquire the physical characteristics of the subcrustal material. There is probably no sharp dividing line in the chemical composition of the two materials. The difference in physical characteristics is probably due to the differences in heat and pressure.

There is also the question as to what happens to the subcrustal material that enters crustal space under an area of erosion. It is probable that the subcrustal material will eventually take on the same characteristics as the material above it. This would practically mean undergoing a

change from plastic to somewhat rigid matter. It is difficult to imagine a sudden change between crustal and subcrustal material. Probably there is a gradual change from rigidity to plasticity. This may take place in a very few miles, or a score of miles. All that we know is that the geodetic data indicate that the average depth to which compensation extends is about 60 miles.

Isostatic Adjustment by Distortion of Spheroid

Matter from land areas is carried to sea by rivers and streams, and subcrustal matter must go back from the sea toward the continent to restore equilibrium; but the flow of material will not be for a great distance. There is no movement corresponding to that of a river or stream. The translation of subcrustal matter will depend on the depth of the yielding matter involved. But in any event, matter lighter than normal is added to ocean areas and heavy subcrustal matter is pushed toward the erosion area.

If deposition is in deep water, then a greater mass of material must be laid down than is pushed aside from the base of the prism of the crust, for the water is displaced by the sediments and it has a density of about unity. Therefore, if the sediments have a density of 2.5, only about 60% of the sediments laid down in deep

water is effective as an added load. This raises a new and very important point. How can the isostatic balance be maintained if only 60% as much mass as the added sediments leaves the lower end of a prism of the crust (or what is equivalent thereto, displaces the subcrustal material)? The answer must be world-wide movement or distortion. As a result of the sedimentation in deep water the ocean basins will be made smaller by about 46% of the volume of the sediments. The amount of water remaining constant, it must have its surface raised above its former position. This will result in an increased load on all parts of the ocean bottom.

The total land area of the earth will be too light by an amount equal to the weight of water displaced by the sediments. The only way in which the land areas can be compensated for this is for there to be a downward movement under the whole ocean area sufficient to restore the isostatic equilibrium of the crust under land and water areas.

Where the crust of the earth is contracting below the sediments at such a rate that the upper surface of the sediments does not increase in elevation, the above phenomenon would not occur. There would be no displacement of the water by the sediments, and consequently no increase of load over ocean areas outside the sedimented area.

Much of the sedimentation of past geologic periods has taken place in shallow water, which has remained shallow during the whole of a period. But there must be many areas where there are no downwarpings independent of that caused by the weight of the sediments. It is these areas that throw out of isostatic equilibrium the ocean and continental areas. It would appear that the only rational process of restoring this equilibrium would be a distortion of the whole sphere, lowering the ocean beds, and raising the continents. But how much would this amount to? Let us take a concrete example, an extreme or even an impossible one. Suppose the amount of sediments, of 2.50 density, laid down in deep water along an ocean margin, to be 3 miles in thickness on an average, 200 miles in width, and 1500 miles in length. Assume 3.15 as the sub-crustal density. The volume of the sediments would be 900,000 cubic miles. The sediments would displace only 360,000 cubic miles of water, for the crust would sink about 2.1 miles under the added weight. As the water surface of the earth is 140,000,000 square miles in area, it is seen that the average depth of the water would be increased 0.0026 mile, or about 14 feet. That amount of water is equivalent in mass to about 5 feet of rock of a density of 2.7, which is the amount to which land areas would be put out of balance by the deposition of 900,000 cubic miles

of sediments in deep water under the conditions assumed.

If the land and water areas of the earth were equal, a lowering of the ocean bottoms and a raising of the land areas one half the 5 feet, or 2.5 feet, would exactly restore the balance. But the land area is only 30% of the earth's surface; therefore, a sinking of the ocean beds 30% of 5 feet, or 1.5 feet, would restore the balance of the crust under the oceans and continents which had been disturbed.

The above illustration gives an idea of the amount the earth's crust would have to be distorted to restore the isostatic equilibrium. The amount is so small that it is possible that the rigidity of the earth may be able to withstand the stresses set up by the shifted load. But on the other hand, the observations for earth tides and for the variation of latitude indicate an elastic yielding of the earth under the tidal forces of the sun and moon, and under the accumulated load of snow on land areas during northern winters. The increased weight of water on the ocean bed would undoubtedly result in an elastic deformation of the earth which might be transformed to a plastic one with the lapse of time. In spite of any distortion of the sphere to restore the isostatic equilibrium of the earth's crust after disturbance due to the deposition of sediments in deep water, the amount of change in the sur-

face of the earth at any one place would be so small that it could not have any effect on any of the major dynamic and structural phenomena involved in the formation of mountains and plateaus, or in the down-warping of an area once occupied by elevated land.

CHAPTER VII

THE INFLUENCE OF ISOSTASY ON GEOLOGICAL DEDUCTIONS

ISOSTASY was treated in ten papers presented at a symposion on that subject at the annual meeting of the Geological Society of America in December, 1921; the papers appeared in the Bulletin of that society dated June 30, 1922.

In the paper by H. O. Wood, entitled "Some Considerations Touching on Isostasy," page 306, is this statement:

> A figure of speech may here serve a useful purpose. In the chronicle of the earth geodesists have read off—may we say glibly?—a single sentence or phrase *recently written and undefaced,* while geologists must decipher innumerable fragmentary letters, words and phrases, found here and there in the tattered pages of a book of encyclopedic dimensions scarcely a line of which has escaped mutilation. By far the greater part of this book has been destroyed during the writing of it, and of what remains only a small portion has been deciphered and interpreted, some of it erroneously, without doubt. Nevertheless, since no one geologist can personally examine more than a very small fraction of the fragmentary remains he *must* accept, for the rest, the readings of his colleagues. Small wonder that there is a diversity of interpretation and opinion; that even a single worker may happen upon phrases which seem to stand in conflict. Notwithstanding all this, there has

> come to be a consensus of opinion in many matters that have seemed clear and consistent which would appear to become uncertain and of doubtful consistency if they must be brought into strict accord with the meaning expressed in the single undefaced phrase pointed to by geodesists. The geologist is thus in something of a dilemma. Must he review and reconstruct his whole philosophy of earth dynamics, or, to shift the figure, is it possible that the geodesist, in pursuing a straight and level short cut to his destination, has missed a good part of the scenery? Granted the geodetic facts, must these be accepted and interpreted narrowly, or are there alternative ways to utilize them? About all this whole books must yet be written. It is not easy to select a few clear vital principles to illumine a brief discussion; but it is sure, nevertheless, that geologists must *endeavor* to reconcile, so far as possible, the interpretation of their multitudinous and somewhat vague observations with that of the few but precise data of geodesy.

The above statement presents the problem of the earth in a clear-cut way. In fact it would be extremely difficult to improve upon it. The geodesist is confronted with the field evidence collected by the geologist, and the latter must not do violence to the principle of isostasy, which requires an exceedingly weak crust.

Another quotation from Wood's paper, page 309, will help to set the earth problem before the investigator even more strongly:

> A second point—a very obvious one—that the present writer would lay stress upon is that every earth prism, down to the incipient yielding, is *contained* and constrained by those which surround it, *except at the surface,* probably more effectively than any like control in

laboratory experimentation. Though we know it well, we must not forget, even momentarily, that the earth is a globe, and this outermost fairly rigid layer of it a continuous spherical shell. Therefore, it is hardly legitimate, especially in thinking of the isostatic problem, where the whole earth is involved, to consider elements of the shell as plane slabs with free boundaries, or with hypothetical abutments of absolutely rigid matter which may be supposed to apply stresses from without upon the edges of the slab. Nor should these elements be thought of as flat domes unsupported beneath, with free boundaries, or hypothetical abutments like those specified for the slab. For example, there is no doubt that such domes, if unsupported below or at the sides, would slump down under their own weight, even when of small area; and either domes or slabs might, if standing alone, break or shear, and thus fail to sustain or transmit horizontal stress imposed from without. But it seems not to be a necessary consequence that elements of a continuous spherical shell of the earth, resting upon and confining the potentially yielding matter beneath, and everywhere affected equally by the centrally directed gravity field of the earth, must slump or crush or otherwise fail to sustain and transmit horizontal—that is tangential—stress, until this has become so great as to bring about failure localized in the weakest elements. When there is deformation of one or more elements, this must, of necessity, involve some change of configuration, molecular if not molar, elsewhere in the outermost shell, with compensatory readjustments in the subjacent layer capable of ready yielding; for there are no void spaces worth mentioning in the potentially yielding region, and any other means of accommodation of augmented downward pressure in one region means either uplift elsewhere, or further increase in the hydrostatic pressure tending to compact the subjacent material (unless there is storage of energy with endothermic reactions). If a mountain mass or a continent

sinks because it is too heavy to float at the level it has attained, something else must rise or there must be changes of conditions in the depths.

So, if the earth's radius undergoes shortening throughout a given interval, whatever the cause of this, . . . the peripheral shell must decrease in area. This requires either uniform thickening, or regional distortion and wrinkling, or both thickening and distortion together in some combination. Of these possibilities wrinkling is positively observed, though it is not positively proved to be due to this cause. To produce wrinkling *under these circumstances* tangential stresses must in some way bring about translation of material towards the wrinkling areas, which will be, at any particular epoch, the weak prisms of the outermost shell.

Any hypothesis advanced to explain the major surface changes must not violate the fundamental physical or mechanical principles outlined in the above quotation from Wood. He concludes his paper with the statement:

It appears possible to bring conceptions of the extreme isostasist and the most conservative students of earth dynamics into much closer harmony without doing violence to the fundamental views of either group. Nevertheless, it is clear that certain of the dynamical concepts appealed to in geology are in need of fresh and critical scrutiny in the light of physics and the properties of materials.

The paper by Harry Fielding Reid, entitled "Isostasy and Earth Movements," presented at the Symposium on Isostasy, presents data which will be useful to the student of the earth. He says that isostasy could not be proved by geologic ob-

servations, but only by geodetic data in the form of deflections of the vertical and values of gravity. He states (page 318):

> But the principle of isostasy is of great value. It bears some analogy to the principle of conservation of energy in the physical sciences. It does not always tell us what earth movements will take place, but it tells us that these movements must be of such a character that the amount of matter underlying a given area of the earth's surface is never materially increased or decreased; and if there be a transfer of matter at the surface by erosion and deposition, by folding of the strata, or by any other means, then there must be a corresponding subterranean transfer in the opposite direction.

After discussing the adjustment to restore equilibrium disturbed by erosion and sedimentation, he says:

> If the earth does yield in this way, it follows that the earth has always been in isostatic equilibrium. Some geologists will not admit this; they contend that we are now in a period of mountain building and of great disturbance, which permit the adjustment, but that this was not true in former geologic times. So far as I know, the objection is based on the contradiction to two hypotheses and not on the opposition to facts. The hypotheses are: (1) That mountains have been raised by the compression of the strata, and thus extra matter has been squeezed into them, and (2) That the earth is too rigid to yield to forces developed by the transfer of surface material.

Reid gives instances of vertical uplift without crumpling. He holds that the Appalachians, which were strongly folded and faulted at the

end of the Carboniferous, were reduced to a peneplain in the Cretaceous, and then were raised in the Tertiary into a broad low arch. Their present topography he holds is due to carving by erosion.

Reid believes that the Andes were elevated after the strata had been folded. He concludes that the folding and some faulting of the Himalayan rocks occurred before their uplift. Reid's views on the relation of isostasy to peneplanation is of interest:

> It has been argued that during a state of peneplanation there has been no movement of the area which was being gradually worn down by erosion, and therefore if it were in isostatic equilibrium before the erosion, it could not be afterwards. But this is begging the question. According to the principle of isostasy, there must be, during the erosion, an influx of matter below (with an unknown lag), to keep up the equilibrium. This would cause a slow elevation of the region, but at a rate less than the lowering by erosion, because the inflowing matter would have a greater density than the surface matter removed. The lag could not be very great, for regions now undergoing active erosion do not show a material defect or excess of gravity. I know nothing that renders this point of view unsound.

The conclusion of Reid's paper presents a difficulty, hard to surmount, to the student of the earth who would ignore isostasy and deny the formation of mountains by crustal expansion. It reads:

> If we reject the principle of isostasy and its corollary,

that mountains are raised by the expansion of the underlying mass, we must believe that they are raised by material being forced in under them from below; for it has been shown that many ranges are not raised by simple compression. This brings with it certain implications. It grants the possibility of subterranean flow and weakens one of the objections to isostasy. As the mountains of the present are in isostatic equilibrium with the rest of the world, the region where they now are must, before the influx, have been in defect by an amount at least equal to the mass of the mountains now above their former level; and this defect must have existed in a region where not only had thousands of feet of sediments been accumulated, but into which still more matter had been forced by the earlier folding. No such defect exists anywhere in the world at present. The plain of the Ganges, which resembles closely the Appalachian trough shortly before the folding, shows no defect of gravity that is not due to the local low density of its deposits. Is it reasonable to believe that a region where matter has been massed to such an extraordinary amount should be the very region to be so extraordinarily in defect? And that, at the time of the elevation, exactly the right amount of matter to produce isostatic equilibrium should be forced into it? And, moreover, that there was a near-by region with just the right excess of matter, which it gave up to the mountain area by subterranean flow, remaining itself in equilibrium.

If we refuse to apply the principle of isostasy to the past, we reject the principle, so fruitful in the history of geology, that we must interpret the past in the light of the present. This principle does not require us to assume that conditions were always as they are now, but it does require us to apply to the past the processes and principles now in force, and only to modify them in the face of definite evidence. And what definite evidence is there opposed to the general principle of isostasy? I know of none.

One of the papers presented at the Symposium on Isostasy was by Sir Sidney Burrard, for a number of years the Superintendent of the Trigonometrical Survey of India. The title of the paper is "Folding of Mountain Ranges—The Argument from Isostasy." By his researches Burrard has done much to place isostasy on a firm footing. His paper indicates that he holds to the idea that mountain systems are caused by vertical movements. He says in part:

> If this granite range (of the Himalayas) had been standing alone, its vertical origin would never have been questioned, but the sedimentary rocks on its southern flank have been folded and elevated. On the other hand if these folds had been standing alone, and had been unaccompanied by the granitic outbursts, geologists would have felt little doubt that the mountains had been raised by horizontal compression of the crust. The granite outbursts and the horizontal folds are in juxtaposition. The problem now presented to us is: Has the vertical uplift of the granite been incidental to the horizontal compression, or has the folding been incidental to the vertical rise of the granite?
>
> Bowie holds that the folding has been incidental to the vertical uplift. A strong argument in support of this contention is that the folded sediments are inferior in height and mass to the granite intrusions with which they are in contact.
>
> If we examine the geological section drawn across the Himalayas, the granite appears to be the main factor; in large scale sections of subsidiary features much folding has been shown, but these folds are superficial and local; their span varies from a furlong up to a mile or two, while the base of the Great Himalayan Range is 40 to 50 miles wide; by no stretch of imagination can

> the Great Himalayan Range be described as a fold of the earth's crust.
>
> Moreover, even among the sedimentary rocks their folding is not so much in evidence as their tilting and faulting; the strata are neither arched nor curved to the same extent as they are tilted and fractured. On the flank of the Himalayas the inward dip of the strata toward the main range without curvature is a remarkable and impressive phenomenon. Bowie's explanation of the Appalachian [1] system appears to me to fit the observed facts of the sub-Himalaya zone.

Although he was an advocate of only regional isostasy, Barrell recognized the necessity of having a decrease of density under the Colorado plateaus in order to account for their uplift. In part I, "Strength of the Earth's Crust, *Journal of Geology,* January–February, 1914, page 35, he makes the following statement:

> There are difficulties, however, in using ancient base leveled surfaces now upwarped as measures of the previous stress. It is known that a region like the Colorado plateau, which now stands markedly high, tended to lie near sea level from the beginning of the Paleozoic to the end of the Mesozoic. Presumably a decrease of density within the zone of isostatic compensation has taken place here during the Cenozoic, and the uplift has accompanied or followed the internal change.

Quotations from many books and papers could be added to those given above to show that students of the earth consider that at least parts of the earth's surface now above sea level owe

[1] American Journal of Science, July, 1921, page 17.

their elevation to vertically acting forces. But by far the greater portion of geologic literature favors uplift as incidental to horizontal compressive forces.

I believe that any one who gives the geodetic and seismic data the careful consideration and the weight that are due them, must arrive at the conclusion that the predominating movement has been vertical, with the horizontal movements evidenced in faulted, folded, and distorted strata as incidental.

Many of the mountain systems now existing have been up and down more than once. With each movement in either direction there will be crushing, crumpling, and the other phenomena observed in a mountain area. It seems to be generally held that mountain systems occupy regions which previous to uplift were the marginal belts of oceans or of inland seas.

The deepest sediments are not laid down in continuous sheets of vast horizontal extent—they are piled up at the mouths of rivers, or are distributed by water currents in narrow belts along the coasts. The rivers change the locations of their mouths, empty their sediment laden waters at different places at different times. The sediments thus accumulate in a very irregular way. As the deltas are formed the sediments are carried farther and farther out to sea. While all of this is going on there may be a sinking of the

surface, on which the first sediments of the region were laid, by contraction of the crustal materials below. This surely happens if the present sedimentary area were once a mountain region. The initial formation of the geosyncline is independent of the pressure of the sediments. Then there is elastic compression of the crust by the weight of the sediments, but this will be small in amount. The greater part of the sinking of the sedimentary area will be due to the weight of the sediments. The sinking will vary greatly from place to place. The movement will be at different places at different times, and will be greatest under the greatest thickness of sediments.

The rigidity of the crustal materials resists downward movement under the weight of sediments. There is especially much shearing and frictional resistance at the sides of the areas that are being overloaded. That these resistances are overcome is indicated by the nearly perfect balance of the crust under sedimentary areas.

During the subsidence there will be faulting and distortion of strata. Horizontal movements of the unconsolidated sediments will occur. If the surface of the geosyncline is irregular, due to previous uplift and erosion with fragments of ancient tilted strata, over-thrusting or underthrusting may occur. At least some of the breaking and folding that may be seen in an uplifted

area may have occurred when the sediments were deposited.

After the sedimentary area goes through the cycle and again becomes an area of uplift, it will have undergone much distortion during the growth of mountains and foothills. The uplift will occur at different places at different times. The forces may temporarily cease to operate within a prism of the affected crust, while forces develop in other prisms; then the force will appear again in the first prism and cause further movements upward of its surface. There is shearing and frictional resistance between any prism and those surrounding it which tend to prevent upward movement unless the forces are equally active in each.

This movement to form an uplifted area, where previously there had been sinking from contraction and the weight of the sediments, will result in much breaking and deforming of rock.

Then there is the continued uplift as erosion lightens the prisms of the crust under the elevated region. This uplift continues until the region has been base-leveled. The greatest amount of uplift occurs after a mountain system has been formed. No one knows how much denser the subcrustal material is than the surface rocks. If 80 feet of subcrustal material is equal in weight to 100 feet of surface rock, then five times as much matter must be eroded from

a mountain area to base-level it, as was present when the mountains were formed. This uplift by isostatic adjustment ever presents fresh materials for the action of the denuding processes. Eventually, most of the recent sediments of the area would be removed, the older sediments would then be exposed and carried away, and then even the igneous rocks would be exposed. In old mountain regions one may find outcroppings of pre-Cambrian strata and igneous rocks, exposed as a result of erosion and uplift by isostatic adjustment. In young systems the oldest strata and granite peaks should not be so much in evidence, and may be entirely absent.

Mountain systems have various widths, depending probably upon the widths of the zones of sedimentary activity. Let us take a system 200 miles in width. Some parts of the area covered by the mountains will have been depressed from one to five miles by the weight of the sediments and the independent contracting. When uplift begins it will have an upward movement from one to three or more miles resulting from the expansion of the crustal material. Then it will have an upward movement several times the amount of the mountain building uplift, during the period of erosion. Each one may form his own idea as to the total vertical movement there might be in a single cycle extending from the beginning of sedimentation through the sedi-

mentary period, the period of growth of mountains and the period of denudation to base-leveling and the beginning of a new cycle. The order of magnitude might be stated, but no definite figures could be given.

Then there is a second complete cycle, and perhaps a third and a fourth. The continent and ocean are no doubt permanent features of the earth's surface since the beginning of the sedimentary age, although each has made invasions of the other. But along the margins of the oceans and inland seas deep beds of sediments have been laid down, and it is above these sedimentary areas that mountains have appeared. Some strips of the earth's surface have been subjected to sedimentation, uplift, and erosion in an endless repetition from the beginning of the sedimentary age.

With a mountain system 200 miles in width, and of indefinite length, will there not be sufficient space for the development of horizontal forces growing out of the vertical movements resulting from the loading and unloading of the crust underneath? An uplift involves a greater crustal prism than any single topographic feature appearing on the surface. A peak or ridge is not due to the expansion of material in a small prism directly below it. The uplift follows the line of least resistance, and the movement may be vertical, inclined, or even horizontal, but it

must act from the prism that is undergoing internal change. The only free surface of the prism is its top, and if the resistance there is made too great by previous uplift, and by the quiescence of surrounding prisms, the surface expression of the forces may at times occur in an adjacent prism. There is no way of determining the exact cross-section of the prisms which may be self-contained, but I should think it may be of the order of magnitude of 50 or 100 miles square. These values result from a consideration of regional and local distribution of compensation, and the size of the topographical feature which may not escape compensation. These subjects are dealt with in other parts of this book.

Do Geological Data Conflict with Isostasy?

Isostasy has been proved by geodesists in their attempt to explain abnormalities in values of gravity and deflections of the vertical, but isostasy is a more important part of the science of geology than that of geodesy. Isostasy has been proved only within the past few years, although the geodetic investigations made early in this century showed that it was probably true. Many references to isostasy are now contained in books and papers dealing with geologic subjects, many of which are listed in the "Bibliography of Isos-

tasy," by Adolph Knopf, which appeared in 1924.

Isostasists among geologists were few in number during the twenty years following Dutton's setting forth of the theory. The interpretation of the geological data collected in the field were, with few exceptions, correlated and interpreted in the light of theories based on the conception of a rigid and strong earth capable of supporting continents and mountain systems as extra positive loads, and ocean and inland seas as negative loads. Mountain systems were usually explained as foldings of the earth's crust along lines of weakness by the cooling and shrinking of the center of the earth with collapse of the non-cooling crust.

It was inevitable that the investigator in the field should be, at least at times, influenced by the prevailing geological theories. Evidence that might have fitted into other theories could easily escape notice, or be considered of no value. With isostasy accepted as a scientific principle, it seems necessary to accept the theory that mountain masses and other large masses of rock, which were once below sea level, were elevated by a decrease in the density of the material below. A corollary of this theory is that where an area has been greatly depressed there has been an increase in the density of the crustal material beneath the affected areas.

The only alternative to this theory is the one which holds that there are roots to the elevated areas caused by the collapse of the crust under regionally acting forces, without change in crustal densities. This theory would have been stronger if there had been only elevations of the earth's surface. But great synclines, or troughs, have formed during geologic times where once there were mountains. The roots theory seems to fail when applied to downwarping of large areas.

The proof of isostasy seems to call for the change of density theory to explain great changes of elevation of the earth's surface—the great ups and downs. This theory, like all others, may have to be modified or abandoned in the future as data accumulate and investigations proceed, but some working hypothesis must be used or no progress can be made, and besides something must be brought forward to replace the collapse theory, which seems to have failed to meet the requirements of geodetic and seismic data.

Is it probable that much of the evidence of movement and rupture of strata observed in the field can be fitted into the theory of uplift by decrease of the density of crustal material below the areas in which the data are collected, just as well as into the collapse theory? The field data are no doubt accurately observed and reported

by their collectors. It is believed that if these data do not seem to conform to the principle of isostasy and its corollary, the theory of vertical movement, the trouble is in the interpretation of the data, not in the data themselves.

Take over-thrust data, for instance; if a movement of strata brings the older above the newer, which strata did the moving? Was it the older, or the newer? If the former, there was an overriding, or over-thrust; if the latter, an underthrust. Again, was the movement from the low ground, the foothills, or even beyond them toward the center of the uplifted area, or was the movement outward toward the foothills and the plains beyond?

There is a decided difference of opinion as to the direction of movement involved in the change in the chronological order of strata. This is a big and important question and needs searching investigation. Again, there are the inclined strata exposed on slopes, along the bluffs of streams and rivers, and in highway and railroad cuts. Are they evidence of great arches which bridged broad valleys, or of troughs extending without break under the valleys? May they not be merely the fragments of ruptured strata which have been given inclined positions as the isostatic adjustment uplifts the crust beneath an area of erosion?

The evidence now available possibly may be

fitted into the isostatic principle, or at least this may be possible if a comparatively small amount of additional field research could supplement the existing data for any given region. The isostasist and the geologist, who hold that the principle of isostasy is established, feel that with complete, or at least abundant geological data for any region, there should be found no lack of harmony between the data and isostasy.

Relation of Gravity Anomalies to Local Structure

A well defined relation between the sign of the gravity anomalies and the Cenozoic and pre-Cambrian formations was recognized by Hayford and the writer when making the investigations of which *Special Publication No. 10* (1910) is a report. While we detected a relation of the anomalies to certain geologic formations we did not at the time sense the full geologic importance of the relation.

In *Special Publication No. 12* (1912), the writer again discussed the relation of the anomalies to certain formations, and showed that the largest anomalies might be caused by extra heavy or extra light material which must extend through depths of at least 15,000 feet. This subject was discussed by the writer in a

paper in the March, 1912, number of the *American Journal of Science.*

In *Special Publication No. 40,* which appeared in 1917, and in *Special Publication No. 99,* which was published in 1924, the writer discussed at length the relation of anomalies to the geologic formations. An abstract of the discussions is given below.

If the density of the upper strata of the crust for large distances laterally from the stations is above normal, the effect on the value of gravity of this extra density will be offset by a deficiency of density in the deeper portions of the crust, if the prisms affected are in isostatic equilibrium. But if the upper abnormal layers are of limited horizontal extent, the gravity values will be increased by extra heavy strata, and decreased by extra light strata. (See Fig. 27.)

The size and sign of the gravity anomalies will depend upon the horizontal extent of the abnormal material, its thickness and density, and also upon the position of compensating excess or deficiency lower down in the crust.

It should be borne in mind that in making the gravity reductions no numerical values are given for the densities in the various layers of the crust below the ocean bottom. It is assumed that the densities of the crustal material below the coastal plains are normal, and that these densities are

modified under elevated regions and under the oceans to the extent that may be needed to compensate the continental and island masses and the deficiencies of density of the water. It is only deviations from normal density in crustal material which are considered in isostatic reductions.

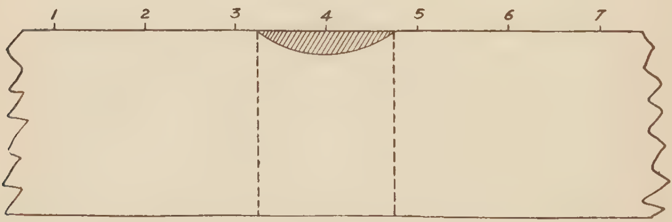


FIG. 27.—The diagram above represents a portion of the earth's crust with abnormally light sedimentary material under station 4. If the value of gravity were determined at stations 1 to 7, it would be found that station 4 would be seriously affected by the light material. Stations 3 and 5 will have their values seriously decreased by the vertical attraction of the light material under 4 but the values will be increased by the counterbalancing increase in density in the lower portion of the column under 4. Stations 1, 2, 6 and 7 would be affected by the compensating increase in density below the sediments but not by the sediments themselves. A mass of abnormally heavy material would affect the various stations, but in the opposite sense to that outlined above.

If there were many gravity and deflection of the vertical stations on and surrounding an area having abnormal densities near the surface, it would be possible to discover by computations the approximate depth and horizontal extent of the extra heavy or light material.

It is evident that the anomalies are not due to abnormal densities in the material above sea

level, since the Cenozoic stations, at which the anomalies are mostly negative, are in general very close to the margins of the continents and at low elevations. The pre-Cambrian stations are likewise at comparatively low elevations, in general less than 1500 feet. If the density of 1500 feet of surface rock be 10 per cent greater than normal the effect on gravity would be only +0.005 dyne. The abnormal densities must extend some thousands of feet below sea level to cause the larger anomalies.

It is not only the pre-Cambrian rock that causes the increased values of gravity, but the igneous rock which is just under the pre-Cambrian. The fact that the pre-Cambrian is exposed leads to the inference that the igneous rock there is nearer the surface than where later rock shows at the surface. It is a noteworthy fact that the pre-Cambrian stations in the United States show, in general, an excess in gravity. The pre-Cambrian exposures are in areas which have been subjected to erosion for long times. The prisms of the crust below must have been elevated by isostatic adjustment and the extra large values of gravity at stations on them must be due to the presence of extra dense matter near the surface. (See Fig. 28.)

The Cenozoic areas have been undergoing sedimentation for long times, hence in order that prisms below might be in equilibrium they must

have been sinking. Since the gravity anomalies above the Cenozoic are, in general, negative, the abnormally light materials near the surface must be the cause of this condition.

For many years it was held by geodesists in India that their country was not in as close equilibrium as the United States. This opinion was based on the many large negative anomalies at

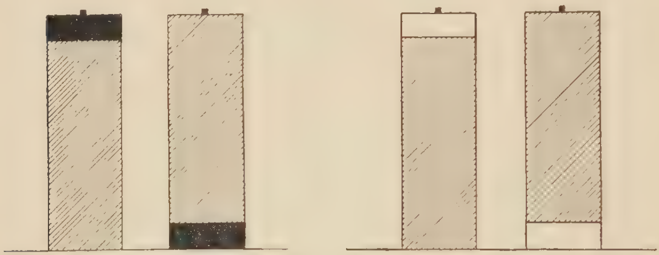


FIG. 28.—The attraction which a column will exert on a unit mass at the center of its top depends upon the distribution of density within the column. If the upper part of column is denser than the mean, the attraction will be greater than normal; and if less dense than the mean, the attraction will be less than normal.

Indian stations. In *Special Publication No. 40* (1917) the writer showed that the large negative anomalies on the recent formations in India might be, and probably are, due to the abnormally light material near the surface. This view was accepted shortly after by Sir Sidney Burrard, at the time Superintendent of the Trigometrical Survey of India, who carried on an extensive investigation, in which he tested the idea that abnormal surface densities cause large deviations from normal gravity. He made a re-

port on his work, which appeared in 1918 under the title "Investigations of Isostasy in Himalayan and Neighboring Regions." He concluded that India is probably in as close isostatic equilibrium as the United States. Burrard's report is a most valuable addition to isostatic literature, and it did much to convince many students of the earth that isostasy is true.

In the United States there are 18 gravity stations on pre-Cambrian rock, and 16 have positive and only 2 negative anomalies. The mean anomalies with and without regard to sign are respectively +0.022 and 0.025 dyne. The negative anomalies are —0.005 and —0.026 dyne. There are only four positive anomalies less than 0.020 dyne.

For the 100 Cenozoic gravity stations in the United States there are 66 negative and 32 positive, and 2 zero anomalies. Only 5 positive Cenozoic anomalies are greater than +0.020, and the maximum is +0.036 dyne.

Of the 127 stations in the United States having anomalies greater than the average, 0.021 dyne, 44 are on Cenozoic and 10 on pre-Cambrian areas. There are 32 stations with anomalies greater than 0.040 dyne, and 17 of these are on the Cenozoic, and 4 on pre-Cambrian. The 8 largest negative anomalies are at Cenozoic stations. The evidence indicates that the 118 stations on the Cenozoic and pre-

Cambrian areas have greater percentages of larger anomalies than the 178 stations on other formations.

In reporting [2] the results of the isostatic reduction of 31 gravity stations in Spain Guillermo Sans Huelin stated that Messrs. Barandica and Milans del Bosch had found that Spanish stations located on pre-Cambrian areas had an isostatic anomaly of +0.047 dyne, while for the stations on Cenozoic areas the isostatic anomaly is —0.033 dyne. It is not stated how many stations are on each formation, though it seems probable that there were more than one in each case. It is thus seen that the gravity data in Spain agree with those in the United States.

There are 16 gravity stations in the United States on Intrusive and Effusive areas. There are 12 negative and only 4 positive anomalies. The mean anomalies with and without regard to sign are respectively: —0.010 and 0.019. This evidence indicates rather clearly that for the United States the exposed igneous rocks which came from depth are not added loads to the prisms of the crust below them. The presence of these rocks at the surface seems to have been due to expansion of the material of the prisms.

The 12 effusive stations in India for which

[2] "La Reduccion Isostatica de Nuestras Estaciones de Gravidad," *Memorias del Instituto Geographico Y Catastral*, Madrid, 1926.

data are available run contrary to those in the United States. Nine anomalies are positive and only 3 negative. The mean anomalies with and without regard to sign are respectively +0.014 and 0.025 dyne.

There are no gravity stations in Canada on either effusive or intrusive areas.

The average gravity anomalies with and without regard to sign for the 296 stations, or groups of stations very close together, in the United States when using the depth of compensation as 113.7 kilometers are respectively: —0.006 and 0.021 dyne. The averages when 96 kilometers is used as the depth are —0.002 and 0.021 dyne. Since the contents of this book are based to a large extent on the writer's reports published by the Coast and Geodetic Survey and papers in scientific journals, in which the depth of 113.7 kilometers is used, and since no analysis of an extended nature has been made of the anomalies resulting from the use of 96 kilometers, it is thought better to use in this work the older value. Detailed data for the gravity stations in the United States, India, and Canada, are given in the following reports, where they may be consulted by those who may wish to pursue intensively the subject of the relation of surface densities to the sign and size of gravity anomalies: *Special Publications No. 12, 40,* and *99,* of the

U. S. Coast and Geodetic Survey, "Investigations of Isostasy in Himalayan and Neighboring Regions," Survey of India, *Professional Paper No. 17*.

Anticlines and Synclines

The evidence and discussions regarding the relation of the gravity anomalies to geologic formations and the effect of abnormal densities on the anomalies presented in the writer's reports and papers led David White, of the U. S. Geological Survey, to request the Director of the U. S. Coast and Geodetic Survey, E. Lester Jones, to have a number of gravity stations established at places below which much was known regarding structure and densities of rock. The request was granted with enthusiasm, as it was realized that valuable results should come from a geologic study of the data to be secured.

White made a study of the anomalies at the Special stations, and at many other stations in the United States located east of the Rocky Mountains. He supplemented the results of the writer's investigations by showing that there is a rather definite relation between the sign of the anomaly and anticlines and synclines. He found that for stations above structural anticlines the anomalies tend strongly to be positive, while for stations located above structural synclines the

tendency is strongly towards negative anomalies. He found this tendency to apply not only to the pre-Cambrian and Cenozoic areas, but to the Cambrian, Peleozoic, and Mesozoic. The relation found by White is due, no doubt, to the fact that under a structural anticline, whether exposed or buried, the igneous rocks, which are denser than sedimentary ones, are close to the surface. On the other hand, under the structural synclines, the igneous rock will be depressed, and their distance from the surface will be greater than normal.

The discovery of White is of great importance since it furnishes a means of studying and working out the structure of an area, and it may be of value in searching for oil. Since the gravity values tend to be high over known anticlines it would be a logical inference that buried anticlines may lie beneath high values of gravity. At least one oil company is now using a gravity pendulum in its explorations. It is also possible that large bodies of ores of high density may be discovered by means of the gravity pendulum.

A paper covering his research was presented by White as his presidential address at the Annual meeting of the Geological Society of America in December, 1922. It appeared in the June, 1923 number of the proceedings of that society.

A Fault or Ridge Once Started Tends To Be Extended

Fault zones tend to have a long extent, more or less parallel to the trend of a mountain system; this is also true of ridges. Is not this a natural consequence of the vertical forces tending to raise an area which had previously been subjected to heavy sedimentation?

The crust affected by the sediments lies in a strip adjacent to the position occupied by the continental shore when sedimentation began. When the crust begins to expand the uplift is very irregular. All parts of the affected crust do not begin to expand at the same time. The sediments were laid down at different places at different times. The beds of sediments were of different thicknesses at different places. In consequence of these conditions the uplift will be quite as irregular in time and amount for different parts of the affected area as was the sedimentation and sinking.

To present the problem in its simplest form, let it be assumed that the whole strip of crust works at the same time and rate, also that the cross-sections of the sedimentary beds are similar all along the strip. Presumably all prisms of moderate cross-section of the affected crust are in equilibrium, and therefore there should be no movement of one prism with respect to others

from gravitational stresses, before uplift begins from expansion. The deepest sediments would not be at the edges of the sedimentary area, nor would they be exactly at the central axis of the area. The greatest activity should be under the deepest sediments, and it is above them that the greatest expansion should take place.

There will be great shearing and frictional resistance to the upward motion by the unaffected crust to the sides of the sedimentary area. There will also be much resistance to upward movement by the upper layers of the crust including the layers of the recent sedimentary beds but presumably the recent materials will be weaker than the beds on which they lie.

For any depth the resistance to uplift should be less under the deep sediments than for any other part of the crustal strip under consideration. The surface of the sediments should be nearly horizontal before uplift begins; therefore, the thickness of the old layers above the isostatic depth would be thinnest under the deepest sediments. When the expansive processes begin operating there will be elastic distortion of the old and recent layers above. If the uplift is of sufficient rapidity fissures will be formed by the tensional stresses or there may be block faulting or a combination of the two. In any event there must be uplift of the surface.

The expansional forces are operating in a region parallel to the axis of the strip, at right angles to it and vertically. It is evident that the movement cannot be downward for this would cause subcrustal material to move horizontally. But the adjacent regions are in isostatic equilibrium, and they will resist the addition of mass. Not only do they already balance the affected strip by their weight but they would resist by the strength of their layers any tendency to bend them up, or to fault them and lift them in blocks. The resistance of the unaffected crust to the sides of the expanding strip will tend to prevent lateral expansion. The material of the strip is undergoing expansion at all parts; therefore, each small prism of it will be re-acting against its neighboring prisms, thus neutralizing the tendency to expand along the axis. The only direction in which the expansion may take place is upward.

Block faulting across the axis of the strip could not result in extensive relative uplift for each prism would undergo its own block faulting, and the relative amount of vertical movement from this cause would be small. Block faulting is likely to occur longitudinally, for the line of prisms over the deepest sediments will be expanded more than the row of prisms to the sides. These will have a tendency to expand more than the prisms at the edges of the strip. There-

fore, it would seem that the block faulting would tend to be parallel to the axis of the strip.

Apparently block faulting occurs when the material of the outer layers of the crust are strong and rigid. They withstand the expansional forces until the elastic limit is reached, and then they break rather than bend and stretch. The horizontal cross section of a fault block is a function of the strength and thickness of the strata affected. Those blocks should have the greatest cross sections which are composed of the strongest rock.

On the other hand when the materials composing the outer layers are not strong and rigid, but are weak and somewhat lacking in rigidity, there should be a tendency under the simple conditions we have assumed for the whole region to arch up, with a smooth surface somewhat similar to the inverted arch of the bed of the sediments. If the material near the surface is very weak and low in viscidity the arch would tend to slump. It could not move axially, for the same vertical movement is taking place all along any line parallel to the axis. The only direction in which the slumping could occur would be lateral. The slumping would begin shortly after the beginning of the uplift, and would continue during the time the expansion takes place. The horizontal extent of the movements would not be great. There would be no flowing of material,

but only a sagging down, which possibly may result in the formation of ridges. Parallel ridges cannot be the result of regionally acting forces (see page 207); therefore, they must be due to local forces. These forces must be acting from high toward lower areas.

It is improbable that the slumping of the material of the outer layers takes place in the surface rocks; these should break and crush. The slumping to form ridges must apparently occur at a depth of a mile or more. If a folded system were not subjected to erosion before maturity, it is probable there would be faulted, crushed, and upturned strata over the ridges. The smooth ridges would appear after the surface strata had later been removed by erosion.

No such ideal trough filled with sediments, like the one discussed above, occurs in nature. The shape of the bed under the sediments is irregular, but there probably is a more or less continuous line running through the deepest sediments, and this line probably does not deviate materially from parallelism with the central axis of the sedimentary zone.

The simple movements postulated for the ideal trough would not occur, but the fundamental principles would not differ. The only direction free to the expansion would be upward. Extensive block-faulting and distortion could not occur at right angles to the axis of the

area; they could occur in lines parallel to the axis. In the actual case should a longitudinal fault develop in one prism, it is probable that it would be continued into or across a contiguous prism, and so on for some distance. If, however, two prisms were to be more active or start upward movement before the prism between them, each might develop a fault zone of itself, and the prism between would be affected on each side, and the final fault zone for the three might not be continuous.

It seems to be certain that a break in the earth's crust would have effects somewhat similar to that of materials with which we are familiar. A small tear in a sail during a storm will, unless immediately repaired, grow in extent. The sail will not fail in many places, but along the first break. A bar of steel, of uniform cross section, subjected to bending may be broken at any point desired by filing a shallow groove at that point. Many examples could be given of materials failing along a line from a small break or tear. The earth's materials near the surface, no doubt, act in a similar manner. May this not be the reason that fault-zones and ridges tend to be continuous and parallel to the general trend of a mountain system?

In addition to the uplift to form the mountains there is great uplift to restore the balance as erosion proceeds. This uplift will also cause

much faulting, and possibly also folding, but the folding would not occur in the surface rock. This faulting and folding would have directions conforming in a general way to the axis of the erosion area.

Isostasy and Earthquakes

The principle of isostasy calls for a local cause for at least each of the major changes in elevation of the earth's surface, and since earthquakes seem to be surface phenomena, it would follow that the causes of earthquakes are local.

Had not the geodesists, when attempting to use triangulation and astronomic determinations of latitude to derive the figure of the earth, proved that the earth has a weak crust, the seismologists would probably have proved it somewhat later. It has been estimated that from 5000 to 8000 earthquakes are recorded yearly by the seismographs now in operation. It is likely that there are many more small quakes which are not within the range of the existing stations. Only a small percentage of the quakes are felt by man, but even the large ones cause only small horizontal and vertical surface changes. No statistics can be given as to the length of the zone which is faulted during the larger earthquakes, but it is believed only occasionally to be greater than 100 miles.

The seismologists have not determined the limiting depth within which earthquakes occur, but few of them believe that the depth is greater than 100 miles. From the viewpoint of the isostasist the limiting depth should be the lower limit of the earth's crust, which must be slightly lower than the computed depth of compensation, 60 miles. If the rigidity of the crustal material decreases with depth and is almost zero at its lower limit the greater part of the earthquakes should occur in the upper half of the crust.

We may conclude from the seismologic evidence that the earth's crust is very weak, and that the causes of earthquakes act locally. This conclusion is in no way in conflict with isostasy. Earthquakes are caused by the breaking of material having residual rigidity. The crust is composed of such material, while the sub-crustal matter, or at least the upper part of it, is quite plastic to stress differences acting for long times.

The forces which cause earthquakes are probably the same as those which cause surface changes. These are due to:

(1) The weight of sediments forcing down the crust beneath them.

(2) The influx of sub-crustal matter into crustal space to restore the equilibrium of crustal prisms which have been lightened by erosion.

(3) The expansion of crustal matter which had been forced down, and subjected to in-

creased temperature, by the weight of sediments.

(4) Contraction of the crustal prisms which have been forced upward as erosion removes material from their surfaces, and later cooled.

The quakes which occur near active volcanoes would seem to fall in the third class, since volcanic activity should, under the isostatic principle, result from expansion of the crust beneath them.

There may be other forces operating to cause surface changes and earthquakes, but the four mentioned above seem to meet all the needs of the isostasist.

There is movement of material below the crust to restore isostatic balance disturbed by erosion and sedimentation. The layer within which this movement takes place is probably a thick one. If it is, the horizontal movement of any unit mass would be small, a few miles or tens of miles, rather than hundreds or thousands of miles. The horizontal movements occur in plastic matter and it is probable that only slight, if any, disturbance is caused by them at the surfaces of intermediate prisms already in equilibrium.

Isostasy and Volcanism

The values of gravity on volcanic islands tend to be too great, but this is probable due to the

presence of material of greater density than normal near the surface. There is no way of determining the density of the material of an island pedestal, but it probably is greater than 2.67, the value used in the isostatic reductions. It does not seem to be possible that the prism of the crust under a volcanic island has greater than normal mass. Its surface, in many cases, stands thousands of feet higher than that of the surrounding prisms, and the stress differences, should the island prism have the greater mass, would be from it toward the adjacent ones.

Since all areas of continents which have been tested are closely in isostatic equilibrium, it seems logical to infer that this condition obtains for islands and the crust surrounding them. On the basis of the isostatic principle, it would seem that some process acting within the crust forces magmatic material to the surface. There are only a few gravity stations on the lava fields of the United States, but the isostatic anomalies at those stations are small. They do not indicate an excess of mass in the prisms on which they are located.

If, as seems to be probable, the outflow of lava on an island or on a continent is due to an expansion of the crustal material beneath the active region, there would not be any increase in the mass of the prism below. The outpoured lava would be an added load on the surface of

the prism, but it would not increase the pressure on its subcrustal base.

The presence of two active volcanoes, close together, on the island of Hawaii is an indication that the processes causing them are not in operation below the crust, nor even very deep down within the crust. If the vents of the two volcanoes were connected with a single liquid or plastic mass it would not be possible to have lava flowing from both of them simultaneously. Mauno Loa has an elevation of 13,675 feet, while the crater of Kilauea is only 4040 feet. The pressure of a column of liquid, or even of very plastic, lava 9635 feet in height would be enormous. No outflow could take place from the higher crater if the two volcanoes originated from the same reservoir of liquid material. This subject has been treated very effectively and convincingly by A. L. Day, Director of the Geophysical Observatory of the Carnegie Institution of Washington. The Hawaiian volcanoes have been studied for a number of years by T. A. Jaggar, Director of the Volcanic Observatory at Kilauea. Volcanism is now receiving much attention and, with the principle of isostasy established, it should be possible to make great progress in that branch of geophysics.

It will be interesting to learn whether islands on which there are volcanoes now active, or active until recently, are rising. To be in har-

mony with isostasy, the mass of the island above sea level should be increasing. There may be local sinking under some parts of the island, due to the pressure of the lava on the surface, and there may be uplift of the surface caused by expansion within the crust, which is not entirely relieved by the outflow from the volcanoes and from fissures. Accurate leveling, repeated from time to time, should, after the lapse of many years, furnish data with which to determine whether there is uplift or subsidence of volcanic islands.

Rate of Denudation

An article on Denudation by R. B. Dole and H. Stables, in *Water-Supply Paper No. 234* of the U. S. Geological Survey, 1909, contains very interesting and valuable data which must be considered in any comprehensive study of isostasy and geology.

An account is given of the gauging of streams and the determination of the solid matter in solution and suspension carried to tidal waters. The estimates of the rate of denudation of the area of the United States is believed by the authors to be correct within 20 per cent. The article contains this statement:

> The estimates reveal that the surface of the United States is being removed at the rate of thirteen ten-

> thousandths of an inch per year, or 1 inch in 760 years. Though this amount seems trivial when spread over the surface of the country, it becomes stupendous when considered as a total, for over 270,000,000 tons of dissolved matter and 513,000,000 tons of suspended matter are transported to tide water every year by the streams of the United States. This total of 783,000,000 tons represents more than 350,000,000 cubic yards of rock substance, or 610,000,000 cubic yards of surface soil. If this erosive action had been concentrated upon the Isthmus of Panama at the time of American occupation, it would have excavated the prism for an 85-foot level canal in about seventy-three days.

A rate of denudation of 1 inch in 760 years is one foot in 9000 years. The average elevation of the United States is about 2500 feet. At the rate of one foot each 9000 years, the United States should be worn down in about 20 to 25 million years, if the material above sea-level were an extra load on the crust and there were no process at work to cause an uplifting of the surface. If the age of sedimentation and erosion is one and one-half billions of years and if the rate of denudation has been uniform during that period the amount of matter carried to tide water would have been about 30 miles on an average. The rate of denudation over such a large area as the United States (3,000,000 square miles) will not be uniform throughout. The denudation will vary with the amount of rainfall, the character of the soil and the subsoil, the geologic character of the rocks and stream velocity. It would seem

therefore that much more would be worn away from some areas than from others.

In spite of the rapid rate of denudation the continent now stands 2500 feet above the sea. Sixty times that amount could have been taken away if the rate of denudation throughout the sedimentary age were what it now is.

The earth's crust is in equilibrium. It probably has been maintained in this condition since the beginning of the sedimentary age of the earth. The rate of denudation in the United States is probably a fair average for the whole land area of the earth. The area of the United States, like that of other large portions of the land area of the earth, has been below sea-level when it accumulated vast amounts of sediments. The evidence indicates that all of a continent was not submerged at any one time. Some parts of continental areas have been submerged and have emerged more than once. It does not seem probable that the average elevation of the United States was ever greatly in excess of its present value.

While denudation progresses the isostatic equilibrium is maintained by a movement of subcrustal matter from the space below the area of sedimentation toward that of denudation. The maintenance of the equilibrium greatly retards the base-leveling of an elevated area.

Rainfall During the Sedimentary Age

The average yearly rainfall on the land surface of the earth is close to 30 inches or 2.5 feet. The rainfall in past geologic time has varied for any one place owing to changes in its elevation and to the changes in elevation and configuration of neighboring regions. There is no reason, however, to believe that the average rate of rainfall for the entire land area has been very different from what it now is.

Before the beginning of the sedimentary age there could not have been running water, hence there was no rain. We are justified in inferring that the earth's surface was irregular, but whether the water was present in the low areas, or as vapor above the earth, is not known.

The sedimentary age began with evaporation, precipitation, and the running of water from land areas. It is most probable that there have been no breaks in precipitation for any long periods of time since the beginning of rain fall.

There are numerous estimates of the duration of the sedimentary age, but one widely recognized is of the order of magnitude of 1,500,000,000 years. With continuous rainfall at the present rate during such a period of time, about three-quarters of a million miles of water would have fallen. The rate of 2.5 feet per year would give a mile of rain in about 2000 years. The

water of the earth, if spread out evenly, would cover the globe to a depth of about 9000 feet, or 1.7 miles. The amount of rainfall during the sedimentary age has been from a quarter million to a half million times as much as the water now on the earth.

No matter what the length of time of the sedimentary age, the amounts of evaporation, rainfall, and denudation have been enormous. They must be given their proper consideration in studies of the earth and of the causes of surface changes. As the earth's crust is weak and in isostatic balance, it seems that these three related phenomena are the primary causes of at least the major changes in the elevation of the earth's surface.

Gradual Lowering of Continents and Their Increase in Area

If we assume that the cause of disturbance of isostatic equilibrium can be attributed to evaporation, denudation and sedimentation, with no other independently acting major cause existing, and that the earth's crust is in isostatic equilibrium and has been in that state since the beginning of the present sedimentary age, then the continents should be decreasing in average elevation, and their margins should be gradually extending out into the oceans. In this connection

the margins should be taken as the outer limits of the continental shelves. It is probable that the average elevation of any particular continent may have been lower at some former time than it is now, also that its margins may have been extended beyond where they now are. But the resultant change during the sedimentary age must have been in the direction of a lower average elevation and a greater area.

When matter from a land area has been transferred to the ocean the crust under the denudation area is lighter than normal, and the crust under the area of sedimentation is heavier than normal and the isostatic balance of both portions of the crust has been disturbed. The balance is restored by a horizontal movement of subcrustal matter. It may be assumed that the greater portion of the sediments is deposited in the tidal waters within about 200 miles of the coasts.

The denuded matter may be assigned a density of 2.70, the upper subcrustal matter a density of 3.15 and the crustal matter an average density of 3.00. The surface matter removed is balanced by subcrustal matter somewhat denser. With these densities the lowering of an eroded area would be about 14% or one seventh the thickness of the denuded matter.

This percentage may be lessened somewhat by an elastic expansion of the crustal matter upon the lessening of load and also by an elastic

expansion of the subcrustal matter which enters the normal crustal space to counterbalance the denuded material. But these effects would be small in comparison with the lowering due to the difference in density of the denuded matter and the subcrustal matter which balances its loss.

The compacted sediments laid down in tidal water may be assumed to have a density of 2.70, that of the materials in place before denudation. Fresh sediments probably have a density 10 per cent lighter than this, but by the time very active sedimentation ceases along any coast, the sediments will have assumed a density closely approximating 2.70.

The sediments, if laid down in shallow water will press down the crust below and cause a displacement of subcrustal material equal in mass, but having only about 86 per cent of the volume of the sediments. This will result in the raising of the surface of the earth where the sediments are placed by an amount equal to 14 per cent of the thickness of the sediments.

If the sediments are laid down in deep water the earth's surface affected will be increased in elevation even a greater amount. The sediments displace an equal volume of water of a density of about 1. Therefore, the effective density of the sediments in increasing the load on the base of the crust below will be only 1.70. As the sub-

crustal density is assumed to be 3.15, only about 54 per cent as great a volume of subcrustal matter is displaced as the volume of sediments laid down. Therefore the solid surface of the earth below the water receiving the sediments will be raised by an amount equal to 46 per cent of the thickness of the sediments.

It is probable that after the deposition of great masses of sediments along any continental margin there will be an uplift. This has occurred in the past, for all great mountain systems occupy areas where sedimentation had previously been heavy. This uplift is not accompanied by any increase in mass of the portion of the crust involved.

The elevation of the surface of a portion of the earth's crust is not a permanent elevation, for the reverse process of what caused the uplift will eventually lower the surface. So the elevation of a mountain system along the margin of a continent should not in itself be considered as a factor in the gradual lowering of the average elevation of a continent and in the extension of a continental area. But the indirect effect of the mountains formed above the sedimentary area is to furnish still more sediments to the tidal water area with extension of the continental margins. The direction of movement of denuded matter depends upon the climatic conditions and the

directions of the streams leading from the uplifted masses. But we are justified in assuming that somewhat more than half the matter carried off in suspension and in solution finds its way to the deep waters which lie outside the general outline of the continents.

Should an inland sea have been formed at or about the time that a mountain system was formed along the coast of the ocean, where formerly there had been thick beds of sediments, much of the denuded matter from the mountains would of necessity be deposited in the inland body of water. This must have been the situation with regard to the deposits which later were raised into the Appalachian Mountain system. There was at that time a mountain system to the eastward from which matter was moved to the eastern margin of the then existing inland sea. While those sediments were forming other denuded matter was moving eastward and deposited in tidal water of the Atlantic. It is the latter material which helped to extend the continental area seaward.

Since much of the denuded matter goes to tidal water outside the continental area it is inevitable that the lighter matter deposited in water areas should extend the continental margins, for even though there is a return of subcrustal matter to restore the isostatic balance, the

latter matter has greater density than the deposited material and hence a smaller volume of it is needed to restore the balance.

The first result of the sedimentation would be to extend the continental shelf and decrease the depth of water above it, and the second would be the formation of continental or island masses by uplift above sea-level over the heavily sedimented areas.

A factor in the rate of change in the average elevation of the continent is the different composition of crustal material under different areas. Washington has showed a rather definite relation between elevation and the chemical composition of igneous rocks. The heavier elements are present in greater proportion in ocean areas than in continental areas.

The materials denuded from the continental masses, most of which come from the higher elevations, no doubt have the heavy chemical elements present in smaller proportions than the crustal materials under the tidal waters in which the denuded matter is deposited.

Presumably the heavier elements are present in greater proportions throughout the crust under ocean waters and therefore the matter which moves landward to restore the isostatic balance will have the effect of increasing the average density of crustal matter below the con-

tinental areas and will cause a lowering of the average elevation of the land areas.

The difference in the density computed from the chemical composition of crustal matter under the continents and under the oceans is not very great. Suppose the average elevation of the continent is one half mile and the ocean depth, after allowing for the water condensed to 2.70 density, is one mile. Since the crust is about 60 miles in thickness the difference in crustal thickness under the land and water is only 2.5 per cent of the normal thickness of the crust. The difference in the density of the crustal material under the land and water will also be 2.5 per cent. With such a small difference in density we are led to believe the change in elevation of continents from the above cause will be exceedingly small but it will be persistent in its action, and its effect will always be in the same direction.

It must also be remembered that the subcrustal movement to restore the isostatic balance does not cause matter to move for great distances. The action is hydrostatic to a certain degree. The whole body of subcrustal material extending from the area of sedimentation to that of denudation will be affected but the translation of any specified part of the material will be small, in tens of miles rather than in hundreds or thousands.

If the width of a sedimentary area were 200 miles and the sinking of the crust 5 miles, then 1000 cubic miles of subcrustal matter would have to be displaced for each mile along the axis of the sedimented area. If the subcrustal movement were confined to the upper 5 miles of the subcrust, the subcrustal matter affected would be moved toward the denuded area a distance of 200 miles. There would be a similar motion of all parts of the upper 5 mile layer of subcrustal matter all the way to the denuded area.

Now let the layer of subcrustal matter involved in the restoration of equilibrium be 25 miles in thickness, then the horizontal movement involved in the restoration of equilibrium will be only one-fifth of the width of the sedimentary area or 40 miles. Should the movement take place throughout the upper 100 miles of the subcrustal matter, the horizontal movement would be only 10 miles. It is not known, of course, just how far down in the subcrust the shift of matter to restore equilibrium takes place, but it no doubt is deep enough to make the lowering of the continents very small due to the shift of matter having different density.

It is not the matter which forms the lower end of a crustal prism which is pushed aside toward the denuded area. The crustal matter forced into subcrustal space may retain for some time its rigidity and force the plastic subcrustal matter

aside. It is probable though that it will eventually behave as subcrustal matter, when it has acquired the temperature which is normal to its new position. If its density then should be different from that of subcrustal matter at that depth there would be a local hydrostatic adjustment to relieve the stresses.

An approximate idea of the continental accretions under certain assumed conditions can be given.

The denudation of the United States is at the rate of one foot in 9000 years or 1000 feet in 9,000,000 years.

Assume that this 1000 feet of denuded material is laid down along the outer coast in shallow tidal water, that the density of the denuded material is 2.70, and the density of subcrustal material is 3.15. Assume also that the area of tidal water in which the sediments are placed is 1,000,000 square miles and that the isostatic balance is maintained. The area of the United States is 3,000,000 square miles. The difference in density of the denuded rock and the subcrustal materials is probably about 17 per cent of the density of the former. We therefore should expect a rise of the bottom of the tidal water, in which the sediments 3000 feet in thickness were placed, of about 430 feet.

If the average depth of water over the continental shelves surrounding a continental mass

were 1000 feet, if the area of water in which the sediments are placed were one-third that of the continent, if the rate of erosion were one foot in 9000 years, if there were no sinking except that caused by the weight of the sediments, and if the surface and subcrustal densities were 2.70 and 3.15 respectively, then the time required to bring the continental shelf to sea level could be derived as follows:

The sediments deposited in deep water have an effective pressure of matter of only 1.70 density, since the sediments displace water having unit density. (In deep water there is not the independent sinking that must be assumed for an area near shore where deep beds of sediments are all deposited in shallow water.) As stated on page 142, the ocean bottom in deep water is raised by an amount equal to 46 per cent of the thickness of the sediments. Therefore, should sediments be deposited to a thickness of 1000 feet over a continental shelf having a depth of 1000 feet, the shelf would be raised 460 feet. At the rate of shoaling of 46% of the depth of sediments about 2200 feet of sediments would be required to bring the continental shelves to sea-level. The time required to accomplish this would be between six and seven millions of years.

When sediments are carried to deep parts of the oceans, the bottoms of the oceans are ele-

vated, and the sea-level is raised. The land areas are lowered in elevation because of the erosion, even though balanced by subcrustal matter. The resultant effect will be a lessening of the average depth of the ocean area of the earth, extension of the water area, and a decrease in land areas. But these effects of deposition in deep water are more than offset by the deposition of sediments in shoal water, and the building up of continental shelves to sea-level by sediments. The net result would seem to be a decrease in the elevation and an increase in the extent of land areas.

CHAPTER VIII

PROCESSES INVOLVED IN CRUSTAL AND SUBCRUSTAL MOVEMENTS

Horizontal Versus Vertical Forces as the Cause of Uplift

The idea that the great vertical changes of the earth's surface are due to regionally acting horizontal forces is deeply rooted in geological science; many of those who acknowledge the establishment of the isostatic principle still hold to the horizontal force idea. It is beyond question that horizontal forces have acted in the past and are now in operation. Horizontal movements of portions of the surface occur during earthquakes, and there is evidence that such movements take place quite distant from faults which have been recently active. There were relative horizontal movements along the sides of the San Andreas fault in California as great as 21 feet during the earthquake of 1906. The recent triangulation executed in California by the United States Coast and Geodetic Survey, which covered the same stations which formed the original triangulation of thirty or more years ago, indicates clearly a horizontal movement of

as much as 15 feet for some of the stations, and possibly a greater movement than that for a few stations. The stations are some miles from the San Andreas fault. This subject is discussed in *Special Publication No. 106* of the U. S. Coast and Geodetic Survey, entitled "Earth Movements in California," 1924.

There is folding of sedimentary strata in uplifted regions, and there are overthrusts, or underthrusts which are undoubtedly due to horizontal movements. Many earth students observing the local phenomena involving evidence of horizontal movement interpret them as being merely incidents to the great horizontal movements which form mountain systems. This it seems to me is an extrapolation which leads to incorrect conclusions. No movement of material can take place without an adequate force. How does the force necessary to cause great horizontal movements originate, or if in existence continuously, how did it come into being? The earth itself is the only part of the universe involved to any extent in what is going on within its solid material.

The sun and moon have influences on the atmosphere and the hydrosphere as the earth in rotating exposes different parts of its surface to those two bodies; but these influences are small even on the hydrosphere. Except where the configuration of the shores causes changes of the

water level of from 10 to 50 feet, the rise and fall of the ocean waters, called tides, are small. On ocean islands the range in the tides is seldom more than five feet. As examples may be mentioned the following island tidal stations with the Spring tide range in feet: Bermuda, 4.0; Ponce, Porto Rico, 1.0; Arnel Point, San Miguel Island, Azores, 5.7; Honolulu, Hawaiian Islands, 1.8; Guam, 2.3; Apia, Samoa, 3.2; Havana, Cuba, 1.3; St. Helena, 2.0; Colombo, Ceylon, 2.0.

The sun and moon exert a tidal effect on the solid earth, but the rise and fall of the surface under this effect is probably less than one foot, and besides it is an elastic phenomenon. The effect is a wave motion with no horizontal movement. It is a movement of oscillation and not of translation. The tidal forces are inadequate to change materially the shape of the surface of the solid earth. The forces are not continuous, and they are not cumulative in their results. We should abandon the idea that the tide producing forces of the sun and moon can move continental masses and build mountain systems and island archipelagoes.

Then there is the small force, appealed to by Wegener, and the adherents to his theory, which tends to pull elevated masses toward the equator. The center of gravity of a floating body is farther from the center of the earth than the

center of gravity of the mass of water displaced. Owing to the centrifugal force, due to the earth's rotation, equipotential surfaces at different heights are not parallel, and the directions of gravity, except at a pole or at the equator, through the center of gravity of the water displaced will not coincide with the direction of gravity through the center of gravity of the floating body. As there is a difference between the two directions, there is no equilibrium, but a tendency for the floating body to move toward the equator. The force is exceedingly small, and certainly cannot break apart crustal matter having even slight residual rigidity.[1]

The above principle applies as well to continental and island masses, and in fact to those masses below the oceans which stand above the lowest part of the ocean floor. But the force is extremely small and even though it acts continuously, it would have no effect in rifting a continent. Even should this improbable event occur the force would be too small to distort the continental surface and create mountain systems.

Wegener's book on the drifting or wandering continents is quite convincing in those parts which are devoted to attacks on the old theory of a cooling center and collapsing crust as the cause of earth movements. Those parts which

[1] See W. D. Lambert "Some Mechanical Curiosities Connected with the Earth's Field of Force," Amer. Jour. of Science, Sept., 1921, page 135.

deal with the breaking up of a single land-mass into continents, with islands left behind in the wandering of the disrupted parts, and his explanation of the formation of the mountain systems of the earth, leaves the reader very much puzzled. Wegener's hypothesis was an attempt to substitute something for the contraction hypothesis which has been vigorously assailed during recent decades.

It appears that the earth's surface is not changed by external forces or forces resulting from its rotation.

The explanation of the surface changes which has been most widely adhered to is the contraction hypothesis just mentioned. According to it, the center of the earth is losing heat through the crust to surrounding space, with the crust maintaining its original temperature. The earth must be losing heat through the atmosphere; this is evident from the fact that the temperature of the earth increases with the depth, at least for the first mile and a half, while the average temperature of the earth a few feet below the surface is hotter than the average temperature of the atmosphere. Why should the temperature of the crust remain constant, however, while the center is cooling? No convincing explanation of this phenomenon has been advanced so far as the writer is aware.

According to the contraction hypothesis, the

nucleus is supposed to contract and shrink away from the crust, leaving the crust detached with spaces between it and the nucleus. Then the crust collapses by the thrusting of the arch tangentially to the nucleus.

As the writer understands the hypothesis, there is supposed to be an accumulation of the stress in the crust as the nucleus contracts with spaces left between. Then when the stress becomes sufficiently great the crust collapses, with failure taking place in the weakest parts which are assumed to be where the crust has been weighted down by the sediments. But should these be the weakest places? Originally, the beds of the sediments were at sea-level; therefore, the sediments are an added strength to the crust beneath. Under the contraction theory no crustal matter has been removed, it has simply been lowered.

There seems to be a weakness in the theory, due to the fact that an inverted arch has its curvature reversed. (See Fig. No. 29.) Sedimentary areas have been pushed down to the extent of five or more miles in some cases. If a sedimentary area is two hundred miles across, the center before subsidence began would be approximately 6000 feet above a straight line joining the edges of the area at the surface. After the center of the area had been depressed five miles by the weight of the sediments, and by any

contraction which may have occurred, it would be about four miles below a chord joining the edges of the sedimented zone.

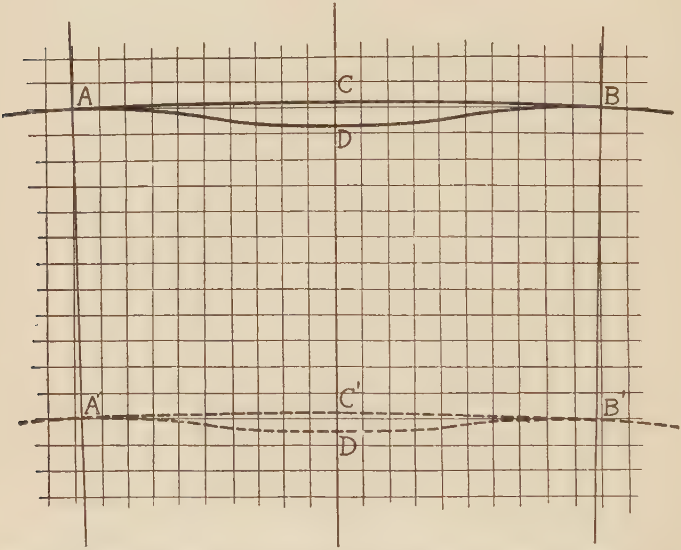


FIG. 29.—This diagram illustrates the condition of the earth's crust under an area of sedimentation. The normal surfaces of the crust are represented by the curved line *ACB* and *A′C′B′*. The vertical scale is 5 miles to the square, while the horizontal scale is 10 miles to the square. The surfaces at *C* and at *C′* are approximately one mile above the chords *AB* and *A′B′*. With several miles of sediments the point *C* at the surface will be depressed to *B* and *C′* to *D′*. In effect, we shall then have an inverted arch, with thick beds of sediments in the trough formed at the surface. According to the contraction theory, when the crust collapses the arch must be reversed to form a mountain system. It would seem more probable that, if there were a collapse of the crust, the arch would be extended downward rather than reversed.

Therefore, in order to force up the crust under the sedimentary area by horizontal forces the resistance of a greater thickness than normal

would have to be overcome, and the arch would have to be reversed.

When an engineering structure is placed in a testing machine an arch is never reversed by forces acting in the direction of the axis of the structure, which may be a beam, column, plate, or arch. Any deviation from a line or plane is enlarged but not reversed. Should the collapsing crust fail at the sedimentary zone, there would be a pushing down of the existing inverted arch, and a folding over of the sides of sedimentary area; the result would be a central trough flanked by parallel ridges. This we do not find in a mountain system.

If there have been voids between the nucleus and crustal shell during past geologic periods there must be some existing now. How does this idea conform to the seismological evidence? Surely no seismic waves could be transmitted through a void. The writer believes there is nothing in the seismologic records of observations to indicate the presence of any dead spaces. No voids exist to-day, and this is strong evidence that none have existed in the past.

Tidal evidence is strongly against the idea of voids. Should the crust be separated even a few feet from the nucleus there would be no ocean tides. The crustal shell would yield under the tide producing effects of the sun and moon. The water and land surfaces would move up and

down together, and no relative motion between them would be noticeable.

The collapse hypothesis has been used to explain the uplift of mountain systems. Great shortening of the circumference of the earth is supposed to have occurred during the sedimentary age of the earth. The hypothesis must also account, however, for the formation of geosynclines, graeben, and ocean troughs. Here stretching is needed.

Again we have block mountains with vertical fault planes, and great plateaus showing no extensive distortion of strata. How could these have been formed by either horizontal stretching or contracting?

In mountain areas the strata involved in the folding, warping, overthrusting, or underthrusting are thin. A thickness of such strata as great as a mile is seldom found. How could such phenomena have been caused under the collapse hypothesis? It may be argued that the material of the crust below moved horizontally, and that the affected surface strata were wrinkled by the undertow, much as the cooling surface of a lava stream is distorted by the flowing lava beneath. But the lava causing the distortion at its surface is liquid or highly plastic. Can we assume the same for the crustal materials involved in the horizontal thrusting? If so, weak strata would be moving upward against gravity with only gravity working on it.

Again, how, under this hypothesis, can the presence of great granite peaks, the highest of all peaks, be explained. They must have moved upward, the up-moving masses acting in the uplift as if they were at least somewhat plastic and lacking in rigidity. Could they have been pushed up against gravity by horizontally acting forces? This seems improbable.

Geologists have devoted years of effort to account for the great surface changes by the collapse hypothesis, but recently students of the earth have appeared who claim that the earth, while losing heat, is not getting colder. Some of them even advance the idea that the earth is really getting hotter. They base their hypothesis on the development of heat in the materials of the earth from radio activity. Among the most active advocates of this hypothesis are Harold Jeffreys, John Joly, and Arthur Holmes. The collapse hypothesis thus has to meet opposition from a new direction.

Aside from its apparent physical and engineering weaknesses the collapse hypothesis must meet the evidence supplied in the form of geodetic and seismic data. The former indicate strongly, many believe conclusively, that the earth has a crust or shell extending to a moderate depth below sea-level which exerts uniform pressure on the subcrustal material. The latter indicate most conclusively that the outer shell of the earth is very weak. The horizontal and

vertical movements of surface material caused by an earthquake are exceedingly small even during the greatest or strongest quakes occurring under land areas. The measurements of earth movement caused by earthquakes at sea are difficult to make, and very few data regarding them are available. The greatest movement on land of which the writer is aware occurred at Yakutat Bay, Alaska, in 1900; it was 49 feet.

The collapse theory calls for a strong and rigid crust, but how can the crust have these characteristics and isostasy be almost perfect wherever tested, and thousands of earthquakes occur yearly with small surface movements resulting from them? It would seem from the evidence that the crustal matter is weak and that it readily adjusts itself to very small stress differences existing within itself, and in the upper portion of the subcrustal material.

The principle of isostasy seems to require a very weak earth yielding to the gravitational forces exerted by comparatively small masses shifted from one place to another on the earth's surface. On pages 104 to 108 is given the evidence to show that a disc of surface material 3,000 feet in thickness and having a radius of about 15 miles does not entirely escape compensation. This is a small mass as compared with that of a bed of sediments deposited along the margin of an ocean or an inland sea, or as compared even

with the sedimentary matter forming the delta of a large river. The delta area of the Mississippi is in approximate equilibrium. (See page 89.)

Mountain areas are in equilibrium, and this indicates that the crust under them is pushed up by sub-crustal material to restore the equilibrium disturbed by denudation. This is a clear indication of crustal weakness.

With such low strength in the crustal materials, as the geodetic and seismic data indicate, there seems to be no possibility of the crust being able to carry thrusts emanating from great distances. If under the collapse hypothesis the nucleus of the earth is shrinking and the crust is detached from it, the crust would collapse or yield locally under the gravitational force. This would result in a general thickening of the crust rather than a thickening along a supposed line of weakness. The crustal matter would remain constant in volume, while the diameter of the shell would be decreased, and the result of the adjustment of the crust to the receding nucleus would be that the crust would become thicker.

We seem to be forced to the hypothesis that the great changes in the earth's surface are due to locally generated forces. The movement of materials under these must be predominantly vertical, with horizontal movements as incidental. There must of course be large horizontal

forces acting to restore the isostatic equilibrium disturbed by denudation and sedimentation, but they act within the subcrustal matter and not in the crust.

If the geodetic and seismic data lead us to conclude that the crust is weak, and that at least the major changes at the earth's surface must be due to local and vertically acting forces, there should be geologic evidence of this. The writer believes much evidence could be and in fact has been found to support this idea.

It seems to be impossible that any voids could exist more than a very few miles down from the earth's surface. The experiences in deep quarries and in mines show that rock yields to stress differences resulting from the removal of materials. Except for the porosity which may exist in rock a few miles down there is no space unoccupied by rock.

There are many valleys, called graeben, which are clearly the result of vertical movement. In them there is no indication of movement caused by horizontal forces. The graeben floors did not sink into voids, and their sinking probably was not due to excess weight of materials. It is probable that the cause of the sinking was contraction of the crustal matter below with increase in density. The isostatic balance was not disturbed

Then there are the ocean deeps or troughs close to and paralleling coasts of continents, or

the axes of chains of islands. These could not have been caused by compressive horizontal forces; nor could they have been due to tensional forces. Should there be regionally acting tensional forces the crust could not well be stretched and thinned locally. There probably would be a tearing apart of crustal matter along vertical or inclined planes leaving rifts into which nucleal matter would flow. Besides, should rifting occur from world wide tensional forces the rifts would extend for greater distances than are found in the ocean deeps, The rift once started would form a line of weakness which would be extended indefinitely. The action would be similar to that where a tear is started in a piece of paper or cloth under tension. The ocean deeps have short axes of a few hundred miles, or at most a thousand. The ocean deeps must be caused by local vertical forces.

In mountain regions there is abundant evidence of vertical movement. A noted example is the eastern escarpment of the Sierra Nevada mountains in California. The vertical movement there has been thousands of feet. Vertical and steeply inclined faults are plentiful in most uplifted areas, and it would seem that they are caused by vertical or tensional horizontal forces.

Dutton [2] several decades ago laid great stress

[2] See "On some of the greater problems of physical geology," *Bulletin* of the Washington Philosophical Society, Vol. XI, pp. 51–64. 1892. This paper was reprinted in the Sept. 19th, 1925, number of the Journal of the Washington Academy of Science.

on the necessity of recognizing vertical forces as the cause of much of the surface movement.

Barrell,[3] a profound student of the earth, held to general isostasy as against local equilibrium. He advocated the idea that the earth's crust is very strong and that horizontal forces of a regional nature predominated, but he stated that the western plateau of the United States, which was uplifted with little distortion of strata, must be due to vertical forces.

The late Willis T. Lee was thoroughly convinced that local vertical forces caused the uplift of the Southern Rockies. Lee had spent many years in that region and was familiar with its geological features. In his paper entitled "Building of the Southern Rockies"[4] delivered at the annual meeting of the Geological Society of America in December, 1922, Lee outlined the past history of the Southern Rockies area and described the present condition found there.

A part of Lee's conclusion reads:

> A search for the cause of the building of the Southern Rockies fails to reveal evidence of lateral thrust of sufficient magnitude to account for them by crustal shortening. Field observations indicate that they were formed by vertical uplift. Considering available sources of information, local forces acting within the crust beneath these mountains seem competent to build them without calling on forces operating at a great distance.

[3] See "The strength of the earth's crust," *Journal of Geology,* Vol. XXII, 1914.

[4] *Bulletin* of the Geol. Soc. of Amer., June 30, 1923.

This is entirely in accord with the isostatic principle.

Much has been written on the geology of the Southern Rockies, but most of the papers consider the uplift as the result of compressive stresses. It would require too much space here to give even an abstract of the literature.[5]

The well known planetesimal hypothesis of T. C. Chamberlin also calls for great crustal shortening and horizontal movements of surface material which result in great changes in elevation of the earth surface. This hypothesis calls for a contraction of the earth from continuously acting gravitational forces, while the collapse hypothesis recognises the cooling of the nucleus without corresponding changes in the temperature of the crust, as the primary cause of surface changes.

Rollin T. Chamberlin has this to say in his article, "The Significance of the Framework of the Continents," *Journal of Geology,* Vol. XXXII, No. 7, Oct.–Nov. 1924, pp. 550 and 551.

> The time-honored theory of earth contraction due to cooling has failed to meet the requirements of the case in at least two important ways; (1) The amount of crustal shortening is greater than can have arisen from

[5] Brief articles on the Southern Rockies are: Rollin T. Chamberlin, "The building of the Colorado Rockies," *Journal of Geology,* Vol. XXVII, 1919; on the "Crustal Shortening of the Colorado Rockies," *Amer. Journal of Science,* Vol. VI, 1923. Francis Parker Shepard, "Indications of Important Horizontal Compression in the Colorado Rockies," *Amer. Journal of Science,* Vol. V, 1923.

the cooling down of a molten globe, even under the most favorable assumptions; and (2) During the Tertiary time alone the east-west Eurasian and the North-South American orogenies, besides minor crumplings, testify to scores of miles of crustal shortening within that period of time, and yet we cannot say with certainty that there has been any cooling of the interior of the earth during the Tertiary. The development of heat may have gone on as rapidly as it was lost. It may have even gone on more rapidly. Certainly there has not been enough cooling in the few millions of years involved to account for such shortening. But on the other hand, the planetesimal conception recognizing and requiring strong condensation by re-arrangement under compression in the interior, involves inevitably the mechanism for large scale earth shrinkage. The large crustal shortening demonstrated by the field data is thus natural and is given an adequate theoretical basis which it did not have before.

As the re-arrangement in favor of greater density must go on throughout the globe, beneath both continents and ocean basins, the shrinkage should be general, and the resulting circumferential compressive stresses must develop throughout the entire peripheral portion of the spheroid, though probably not reaching the same intensity everywhere. Strong tangential thrusting stresses would develop beneath both the continental and the oceanic areas. These are the ultimate forces concerned in megadiastrophism.

In the shrinkage process the oceanic regions, being composed of denser material, naturally take the lead in sinking, as has been clearly stated in the textbooks. Though the sinking be general, the smaller and lighter continental areas would be pushed upward by the lateral crowding. These have been treated as segments, the suboceanic masses being the master segments and the continents as squeezed segments between oceanic segments, perhaps working on the wedge principle.

The writer does not feel competent to criticize or defend the planetesimal hypothesis, which gives an explanation as to the manner in which the earth was formed. But it seems to him that the above statement of Rollin T. Chamberlin as to processes at work after the earth came into existence has two points of weakness.

The first is the assumption that the earth continuously shrinks under the gravitational forces within its mass. The pressure on the matter a few hundred miles below the surface is of course enormous, and the pressure increases to the center. It does not seem to be possible, however, that there could have been any elastic deformation or decrease in volume after the earth acquired its present mass in a solid condition. The elastic compression takes place very rapidly and lasts only until the elastic resistance balances the forces acting on the material.

A metal tape subjected to a constant but small tension will continue to elongate, but the volume of the tape does not change. With the increase in length there is a decrease in cross-section.[6]

Since the earth is under gravitational forces of like amount along all radii, the earth will not be distorted radially by them and increase its dimensions at right angles, and it would seem

[6] C. E. Van Orstrand, *Bulletin* of the Geol. Soc. of America, June 30, 1923, pp. 304 and 305.

that the earth would not suffer continuous elastic compression after a very short time after its formation.

Chamberlin speaks of the planetesimal conception requiring strong condensation by re-arrangement under compression in the interior; perhaps he has in mind some chemical or physical re-arrangement of the material elements of the earth. But will a chemical or physical process continue for hundreds of millions of years where there are insignificant changes in gravity, if any, acting on the central mass? It is probable that the contraction from such processes would have ceased soon after the earth's formation. Of course this idea cannot be tested since there cannot be reproduced at the earth's surface the enormous pressures which are exerted on the inner material of the earth. Besides geologic time intervals would be required.

The other weak point in Chamberlin's statement is that the continental and oceanic segments tend to crush each other, and that the continental ones being lighter in density and weaker give way with the great thrusting movements observed in uplifted areas. This idea does not fit in with an isostatic earth. In fact it is in opposition to the isostatic principle.

The earth's outer shell is not strong; it yields readily to shifting loads over its surface. There must be horizontal movement in subcrustal ma-

terials which apparently has little, if any, effect on the surface configuration except in so far as it lowers the crust under areas of sedimentation and raises the crust under areas of denudation. With subcrustal material so weak and plastic to long continued stresses it does not appear that it could act to crush the continental segments.

The seismograph shows that from five to ten thousand earthquakes occur yearly. The geologic observations show that only small changes occur during any one earthquake. These lines of evidence prove that the earth's crust is composed of very weak matter. The depths of earthquake foci have not been accurately determined, but the evidence so far put forward indicate that quakes do not have their origins deeper than about 60 miles below the earth's surface. This is the derived depth of compensation.

The forces postulated by Chamberlin would be dissipated in causing surface changes close to them, and would not be effective at horizontal distances of thousands, or even hundreds of miles.

Movements Resulting from Lateral Thrusting

The theory that a mountain system has been caused by lateral thrusts originating from a distance supposes a very anomalous condition. It

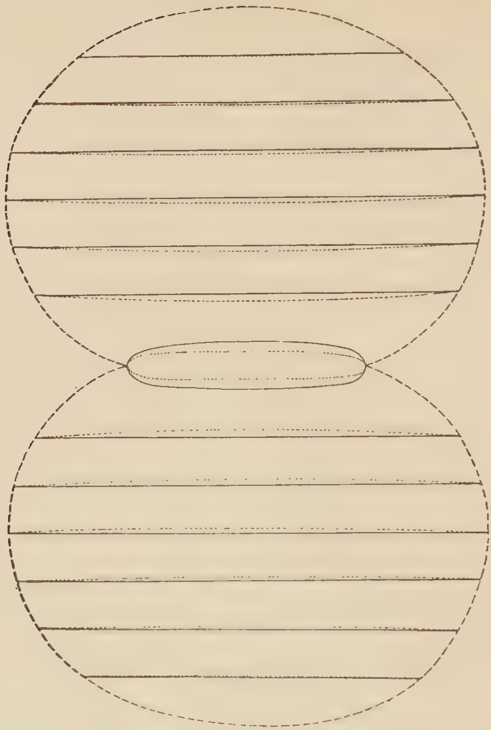


FIG. 30. The full oval represents a mountain area previously an area subjected to heavy sedimentation. Assume that the width of the mountain area is approximately 200 miles and that the length of the system is approximately 1000 miles. Let it be assumed that the full straight lines were marked on the earth's surface, parallel to the mountain system, before the uplift occurred. According to the contraction hypothesis, there would be a movement towards the sedimentary region which would form a mountain system, shortening the distance across the sedimentary area. In order that this might occur, each of the lines which was straight before the uplift began would, after the uplift, be curved. This would imply weakness on the part of the material carrying the thrust; besides, the material to the sides of the mountain system would be expanded or stretched, rather than compressed. Material that is strong enough and rigid enough to carry great horizontal thrusts cannot be so weak as to be distorted in all of its elements while carrying the thrusts.

implies that the earth's crust is competent to carry thrusts that would squeeze up mountains and plateaus, and at the same time that it is so weak that it can undergo the distortion incident to the movement causing the uplift. To be concrete, the Appalachian system is supposed by many to occupy an area that is many miles narrower than the area occupied by the material before the uplift began. Let us assume that the amount of contraction is 20 miles. If the regional horizontal theory is correct, this means that some of the material in the areas beyond moved toward the mountain area as much as ten miles or one-half of the shortening of the base of the mountains, assuming that movement occurred from both sides. If we should consider a number of imaginary straight lines a few miles apart, parallel to the axis of the mountains, to have been drawn on the earth's surface before the movement began, then each of these lines would become bowed during the mountain formation to the extent of making the centers of at least the near ones 10 miles distant from the positions occupied originally. (See Fig. 30.)

This, it seems, is an inconceivable situation because no structure that is so weak as to be distorted to this extent could possibly transmit the stresses necessary to hoist the mountains. But there are other anomalous elements in the theory. A mountain system is of limited extent,

and seldom is the axis of the system more than 2000 miles in length. This distance is about one-twelfth of the earth's circumference.

If one were to cut out a segment from a hollow rubber ball (the segment lying between two circles drawn through opposite points) it would not be difficult to press the edges of the segment together. But suppose an oval shaped piece of the ball were removed, and that the length of the piece were about one-twelfth of the circumference, the closing of this vacant place would have to be by pulling the edges together, and there would be much distortion of the ball in doing so.

Now suppose we should try to close the twenty mile strip, representing the shortening of the width of the Appalachians—would we not have to pull the edges together? The crust, considered competent by the advocates of the collapse theory, would present a solid and unbroken front, and therefore it could not be restricted in its action to a distance along its front of one or two thousands of miles. The earth being spherical it should move farther at the center than at the ends of the space to be closed. If the crust moved forward as a strong unyielding engineering structure, it would have to be sheared from the unaffected crust at the sides.

If the space is closed by thrust from rigid crustal material then there must be some void

behind the moving material or we run into the difficulty of having to shorten the circumference of the earth 20 miles at right angles to the axis of the uplifted region with the rest of the surface of the earth unaffected. But the advocates of the hypothesis may advance the idea that many mountain systems are being upraised at the same time. This would not help matters, for the crust would have to undergo many local distortions and this could not occur unless the crustal material is weak. The crust must be strong or weak; if strong, it cannot be distorted to the extent necessary to close by thrust a space 20 miles in width and 2000 miles in length. If weak it cannot force up mountain systems against gravity, and if the nucleus were shrinking away from it, it would collapse locally, merely resulting in increasing its thickness.

Analysis of the Airy Idea of Isostasy

There are three rather distinct isostatic ideas; the one originated by Airy, now well known as the "Roots of Mountains Theory"; the one by Pratt which postulates a crust having densities varying horizontally; and the one by Wegener, which postulates that the crustal material is only present under continents and islands. The Pratt idea is the one having the greatest number of supporters. It is the isostasy of Dutton, Hayford,

Burrard, Reid, and the writer. It is the one used in deflection of the vertical investigations in the United States and in India, and in gravity studies

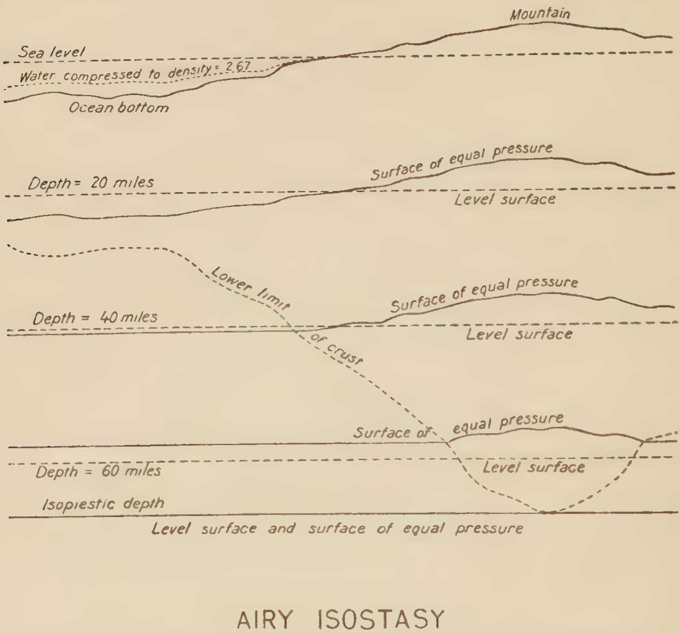


FIG. 31.—For the Airy hypothesis of isostasy, the level surface which is also one of uniform pressure, is at the lowest point to which crustal material extends. The crust within which the compensating deficiencies of density exist is supposed to be thicker under continents than under oceans. The diagram shows the relation of level surfaces and surfaces of uniform pressure. As in the Pratt hypothesis of isostasy, level surfaces below the one that is at the lower limit of the crust will also be surfaces of uniform pressure.

in many areas. Heiskanen has made gravity reductions by the Airy theory, but he has not expressed himself as favoring that one over the Pratt theory. (See Fig. 31.) For the relation of

level surfaces and surfaces of equal pressure for the Pratt isostasy, see Fig. 3, page 9.

While isostasy has been proved, and may now be accepted as a principle, yet the manner in which the compensation is distributed is not known, and, therefore, any system involving this phase of the subject must still be considered a theory. We, therefore, may speak of the Pratt theory or the Airy theory of Isostasy, without implying any doubt as to the fact of isostasy.

In a paper presented in 1855 at a meeting of the Royal Society of London, Airy said:

> I conceive that there can be no other support [for an elevated tableland] than that arising from the downward projection of the earth's light crust into the dense lava; the horizontal extent of that projection corresponding rudely with the horizontal extent of the tableland, and the depth of its projection downwards being such that the increased power of flotation thus gained is roughly equal to the increase of weight above from the prominence of the tableland."

The isostasy of Airy calls for a weak yielding subcrustal material but probably not weaker than is required for the Pratt isostasy. Any theory regarding isostasy must provide for a subcrustal base of low rigidity to stresses acting for a long time.

The Pratt isostasy may be tested by using the printed reports on the isostatic reductions of deflections of the vertical and values of gravity. No such data are available with which to test the

Airy isostasy, but it is possible to make an analysis of this theory which will throw some light on it.

If two icebergs floating in the ocean have different masses exposed we are correct in assuming that the one with the greatest mass above water has the greater mass below. If the exposed masses were in the ratio of two to one, this ratio would represent the relation of the submerged masses.

This principle may be used in testing the Wegener hypothesis of floating and drifting continents, for the matter under the oceans is assumed by him to act almost like a liquid with continental and island masses bearing a strong analogy to the iceberg. The iceberg analogy cannot be used without modification to test the Airy theory, for it supposes crustal material under oceans as well as under continents.

According to the Airy theory, there should not be horizontal variation of densities in the crustal material. The portions of the crust having normal thickness however may be assumed to be composed of layers of different densities, the density presumably increasing with depth.

The best value for the depth to which the isostatic compensation extends under the area of the United States, as derived from gravity data in mountain regions, is 95 kilometers; the value from deflection data also in mountainous regions

is 97 kilometers. The mean of these 96 kilometers (60 miles) is believed to be the best derived value.

The average elevation for the mountain areas of the United States as derived from the data given in the table on page 66, of *Special Publication No. 40,* is 1230 meters (4030 feet, or 0.75 mile). These data consist of the elevations of the gravity stations and the differences between those elevations and the average elevation of the regions within 100 miles of the several stations. The average elevation of the United States is about 2500 feet; therefore, the mountain areas used in deriving the depth of compensation of 60 miles is 1500 feet (about 0.3 mile) above the general level.

In order to compute the thickness of the crust under different elevations according to the Airy theory, assumptions must be made as to the average density of the crustal and upper subcrustal matter. We have no data to work on so the conclusions may have little weight. Let us assume, however, that the material above sea-level has a density of 2.70, that of the crust a density of 3.00, and that of the upper subcrust a density of 3.15.

The mass of a unit column under the mountain areas of the United States may then be represented by the following equation: $0.75 \times 2.70 + 60.0 \times 3.00 = 182.0$.

The mass for the average unit prism for the

whole country down to a depth below sea-level of 60 miles must be the same as under the mountains. We then have the equation:

$$0.50 \times 2.70 + X \times 3.15 + (60 - X)\, 3.00 = 182.0$$

and X (the thickness of subcrustal matter) $= 4.3$ miles. The crust is therefore 55.7 miles thick as an average for the whole United States.

For a unit prism at sea-level the equation would be:

$X \times 3.15 + (60 - X)\, 3.00 = 182.0$, from which $X = 13.3$ miles. The crust in this case is 46.7 miles in thickness.

Let us assume that the prisms of the crust at sea-level have the normal length of 46.7 miles; then the average length of the roots for the mountain areas of the United States will be 13.3 miles. The mass in the unit prism at sea-level may be represented by $3.00 \times 46.7 = 140.1$.

The crust under a water area must be thinner than under the sea-level areas. For a unit prism under one mile of water, we have the equation:

$$1 \times 1.03 + X \times 3.15 + (45.7 - X)\, 3.00 = 140.1$$

The density of sea water is 1.03 and X represents the thickness of subcrustal matter above the 46.7 mile depth. The solution of this equation makes X equal to 13.1 miles. The crust, therefore, is 32.6 miles in thickness and it extends 33.6 miles below sea-level.

By the same method it will be found that the thicknesses of crust under depths of water of 2 and 3 miles are, respectively, 18.4 and 4.3 miles. For greater depths there would be no material whatever of the average crustal density of 3.00. Therefore, there could be no equality of pressure, with the assumed densities, between a prism of the crust at the coast and a prism under more than three and a fraction miles of water.

In order to compute the length of the root of a mountain prism we have the simple equation: $2.70h = 0.15Y$ in which h represents the elevation of the prism above sea level and Y, the length of the root. The constant 2.70 is the density of matter above sea level, while 0.15 is the assumed difference between crustal and upper subcrustal densities.

For elevations of 1, 2, 3, 4 and 5 miles, the lengths of roots extending below the 46.7 mile depth, are respectively, 18, 36, 54, 72 and 90 miles. These values added to the 46.7 miles give thicknesses of crust of 64.7, 82.7, 100.7, 118.7 and 136.7 miles.

Should the average densities of the crust and of the upper subcrust be 3.00 and 3.30, respectively, then the thickness of the crust under the coast will be 53.3 miles.

For heights of mountains of 1, 2, 3, 4, and 5 miles the roots would be 9, 18, 27, 36 and 45 miles, respectively. The thicknesses of the crust

under these elevations would be 62.3, 71.3, 80.3, 89.3 and 98.3 miles.

Under depths of 1, 2, 3, 4 and 5 miles of water the thickness of the crust will be 45.7, 38.2, 30.6, 23.0 and 15.5 miles, respectively.

It would appear from the above calculations of thicknesses of crust under different elevations of land areas, and different depths of water, that the difference between the crustal and upper subcrustal densities would have to be nearer 0.30 than 0.15. But can there be so great a difference in density in the crustal and the subcrustal matter?

For an elevation of 5 miles the root is 45 miles in length, for a difference in density of 0.30. It would seem, however, that the lower part of the crustal matter would form the root. On the assumption that the average crustal density is 0.30 less than that of the upper subcrust, it is reasonable to conclude that the difference in density of the root formed of lower crustal material and the surrounding subcrustal material is less than 0.30. There is probably no sharp break in density at a depth of from 50 to 60 miles below sea level and if there is not, then the computed lengths of roots given above are too small. Also the thicknesses of the crust under the oceans are too great as computed.

The evidence furnished by the density tests seems to be against the Airy theory. But there

is another line along which the Airy theory may be tested. This involves the mechanics of the problems presented by earth movements. The roots of mountains of the Airy theory have been formed by regionally acting horizontal forces which have crushed or squeezed the crustal matter under zones of sedimentation. The collapse of the crust is supposed to have produced both the mountains and their roots.

It is shown above that the thickness of the crust under the coastal plains must be about 50 miles, since the thickness under mountain areas is about 60 miles. Is it possible that a regional horizontal thrust can be carried through the very thin crust under the deep parts of the ocean and crush thicker crust under the coasts? This does not seem reasonable. The weakest zones should be where the crust is thinnest under the deepest part of the oceans.

In order that the roots may be formed, the crustal matter under the sedimentary zones must be very weak. The material must be so plastic that it can be thickened by squeezing. Under this condition the subcrustal matter must be far weaker than the crustal matter in order that the latter may penetrate subcrustal space. This calls for a very weak earth both crustal and nucleal, for equilibrium must be restored after the formation of the roots of a mountain system by a distortion of the whole globe. There is no spe-

cific local space into which the displaced subcrustal matter may go.

But if the crustal matter is weak enough to be depressed into subcrustal space, and the subcrustal matter is so weak as to be pushed aside, there will be little or no strength in the roots.

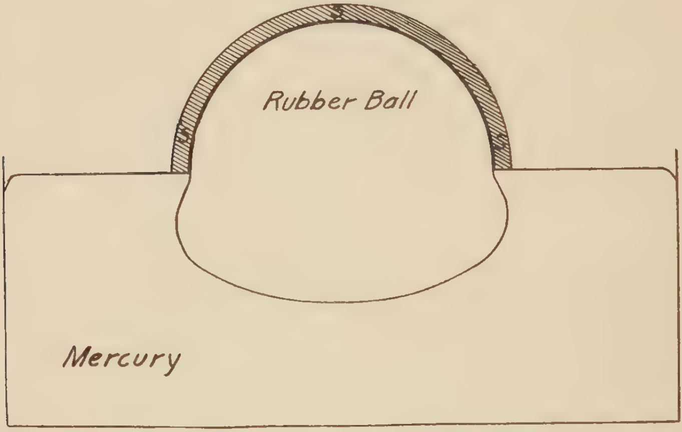


FIG. 32.—A rubber ball, fitted into a hemispherical shell *SSS*, and then pushed down into a basin of mercury, will undergo distortion of the portion submerged. There will be a tendency for any mass of material to be distorted that is pushed down into a heavier material that is liquid or plastic. Material of the earth's crust which may be pushed down into subcrustal space will be subjected to forces which tend to flatten out the projecting material. There would be a tendency for the roots of mountains, required by the Airy isostasy, to be flattened out by the subcrustal matter.

They will be subjected to great gravitational stresses equivalent to the difference in mass of a unit prism of the root and a unit prism of the subcrustal matter, both having the same length. (See Fig. 32.)

For two prisms of the earth's crust the difference in their lengths bears a definite relation to the difference in their surface elevations. If these elevations should differ four miles, the higher prism will extend into subcrustal space farther than the other prism an amount sufficient to balance four miles of surface materials. The upward pressure of the subcrustal matter on the lower end of the root will be equivalent to the weight of four miles of rock of surface density. This pressure seems to be more than the crustal root can withstand, and besides it must be more than the postulated horizontal force which formed the roots. The effect of the upward hydrostatic pressure would be to flatten out or mushroom the root. When this was accomplished the mountain system above would also disappear.

We have strong evidence, in the form of gravity anomalies, to show that the earth's crust cannot support, unbalanced by compensation, a disk of surface material 3000 feet in thickness and 30 miles in diameter. (See p. 104.) The crustal material is weak and cannot withstand a pressure of one or more miles of hydrostatic pressure exerted by subcrustal material. The expression "hydrostatic pressure" is here used in its broadest sense as applying to liquid or plastic matter of any kind. It implies the presence of water, hence some other expression

should be used in speaking of the crustal and subcrustal matter, but what other suitable expression is there? The writer knows of none, and besides the meaning to be conveyed to the reader is clear.

Former mountain areas have been base-leveled, and it is certain that the crust beneath has continued in isostatic equilibrium during the process. At the time the mountains disappeared, the thickness of the crust must have been normal in thickness, the thickness for sea-level prisms. The roots of the mountains will also have disappeared. If there has been no change in density of crustal matter during the erosion period, then an amount of material at least equal in thickness to the length of the root must have been worn away. Under any reasonable assumptions as to densities, the roots under the Himalayan Mountains must be of the order of length of from 40 to 60 miles. If such an amount of material were eroded from that system no sedimentary material would be left when base-leveling had been completed. No such condition has been observed in a region, formerly occupied by a mountain system, which had been base leveled and subsequently elevated.

It may be argued by the advocates of the Airy theory that the Pratt theory presents similar difficulties. This is only partly true, for the difference between surface and subcrustal density

is much greater than that between the lower crustal and the upper subcrustal densities. Under the Pratt theory the amount of erosion needed to base level a mountain area is not so great as that required by the Airy theory.

After an area has been base-leveled and a geosyncline formed, sedimentation of the area begins. But sedimentation cannot continue in shallow water for a long period, unless there is a sinking of the surface which is independent of the weight of the sediments. The writer has seen no statement describing the process by which an area at or near sea-level is lowered under the Airy theory. It would seem that there must be a stretching of the crust with a thinning of those portions which had previously been thickest. This may not be the explanation given by advocates of the theory, but a reasonable explanation should be advanced by them.

The ocean deeps seem hard to explain by the Airy theory. The crust under the oceans is only about one half as thick, on an average, as the crust under the continents, but the ocean crust by this theory must be stronger than the crust under the sedimentary areas, for it must transmit horizontal thrusts to form mountain systems and their roots along the margins of the oceans and of inland seas.

These thrusts must be transmitted through the crust under ocean deeps, for each deep is

parallel to, and comparatively near, a mountain system close to the margin of a continent, or a chain of islands. But the crust under the deeps must be exceedingly thin, and as the theory calls for subcrustal matter incapable of carrying horizontal thrusts, the thrusting must be done by this thin crustal matter.

If the deeps along the Japanese and Philippine Islands existed prior to the uplift of those masses, it does not seem possible that the thrusts could have been carried by the crust under those deeps. This applies also to the deeps paralleling the west coasts of Mexico and South America. If the deeps were formed later than the uplift of the islands and mountains they must have been due to stretching and thinning of the crust and they must have been formed above zones of crustal weakness. But how could they have become zones of weakness when they were zones of strength during the uplift of contiguous zones?

In addition to the weaknesses of the Airy or Roots theory set forth above, it has all or nearly all the weaknesses of the old contraction and collapse hypothesis. The only point in favor of the former over the latter is that it does not violate the principle of isostasy.

The writer is convinced that the Airy theory is untenable. In this book he has assumed that the Pratt theory of isostasy is the only one so far

advanced that is sound and his conclusions, therefore, are based on it.

Effects of Isostasy Adjustment on Crustal Temperatures

To interpret properly the earth movements at and near the surface, we should know the temperature at various depths, and at least down to a depth of a number of kilometers. But this knowledge is denied us, and it may never be disclosed. Speculation and hypothesis can be used to furnish some idea of the temperatures, but at best the lines of attack will be indirect and nothing definite and accurate can be learned.

We have an abundance of evidence as to the temperature gradients for the first half mile below the surface and much data for the second half mile. There is little known about the temperature gradient below that, for the deepest hole drilled into the earth is only about one and one-half miles (near Fairmont, West Virginia).

N. H. Darton presented the available thermal gradient data for the United States in *Bulletin 701* of the U. S. Geological Survey, which appeared in 1920. A fair estimate of the gradient, as derived from observed temperatures in mine shafts and borings, is 50° C. (90° F.) per mile. But this value is only approximate as may be seen by an inspection of Darton's report. The

increase with depth varies from 1° F. for a very few feet, to 1° F. for more than 200 feet.

The maintenance of the isostatic condition of the earth's crust seems to require changes in the density of the crustal material. Under mountains there has been a decrease in density and under geosynclines there has been an increase. It would seem that these changes have resulted from decided changes in temperature. There may have been some other cause but no adequate one has been suggested. The change in the resisting qualities as the depth of about 60 miles below sea level is passed may be due to the increased pressure or to a difference in the composition of the material; but it is the opinion of the writer that the change in the resistance is probably caused by a combination of pressure and temperature conditions.

Few geologists today question the sinking of the crust under a sedimentary area. As a result of the sinking each unit mass of crustal material goes down an amount approximately equal to the depth of sediment above. If the temperature increases with the depth throughout the crust and in the subcrustal material there would be a source of heat to raise the temperature of the crustal materials. To raise the temperature to the extent that would seem to be necessary to make the crust expand and elevate the surface into mountains or a plateau, the temperature just

below the crust must be very great. If the gradient for the first mile is maintained throughout the 60 mile crust the temperature at the bottom of the crust would be about 3000° C. This temperature would fuse any known rock under surface pressure, but the crustal pressure is sufficient to keep solid the material 60 miles down.

In the process which keeps the crust in isostatic equilibrium under an area of erosion the deep crustal matter is brought towards the surface, and in this case it would seem there must be a loss of heat at the upper surface and to the sides of the uplifted material which would finally cause the crust to shrink and form a geosyncline.

In both the processes of uplift, one under sedimentary areas by expansion of the crust, and the other under erosion areas without expansion, there must be a heavy drain on the supply of heat in the subcrustal material.

If the sedimentary age of the earth is about 1,500,000,000 years, and if the rate of erosion has been the same during that time there must have been much up and down movement of the crust under and close to continental areas.

The present rate of erosion over the area of the United States as determined by river gauging and analyses of river waters by the U. S. Geological Survey is an average one foot in

9,000 years. At this rate one mile would be removed in about 45,000,000 years. If the maintenance of the isostatic equilibrium had kept North America above sea-level throughout the sedimentary age, about thirty miles of rock would have been carried to the oceans, at the present rate of erosion. (See p. 185.)

There is abundant evidence, however, that the continental areas have at times been below sea-level. Therefore, the erosion for any selected portion of the United States has not been continuous, but even if the area had been above sea-level only one half of the time of the sedimentary age, the erosion from it would have been enormous.

In this process the earth might have lost an amount of heat equivalent to about 700° C. throughout the 60-mile crust. The surface temperature at the beginning of the sedimentary age was certainly within 100° C. of what it is now. As the exposed surface was eroded the crust beneath received subcrustal matter to counterbalance the loss at the surface. The uprising crust cooled down to normal, then shrunk and took on new sediments at the surface. It sank down to hotter regions, became heated to normal, rose up by the expansion, and then underwent another period of erosion with uplift by isostatic adjustment, and so on. This process will continue as long as rain falls and causes erosion

and sedimentation. Possibly the loss of 700° C., mentioned above, may be too high a figure but at least the loss must have been several hundred degrees centigrade.

If the subcrustal material under areas subject to erosion and sedimentation is losing such enormous quantities of heat, is it not probable that this subcrustal material just below the crust is colder under these areas than below areas not subjected to the alternate erosion and sedimentation? It would seem so. The average temperature of the rock at the bottom of the ocean is not many degrees lower than that of the land surface, possibly from 10° to 20° C. The ocean waters probably do not conduct heat from the earth any more rapidly than the air. If they do not then it would seem that, for any given depth not far below the crust, the temperature under the oceans should be greater than under the continents.

But we have another factor to consider; most of the isostatic adjustment involving movement horizontally of sub-crustal material occurs and has occurred from the margins of the oceans where most of the sediments are deposited towards the continents from which the sediments were derived. There is also a movement from under the inland seas toward the lands surrounding them. Have these movements created heat, and if so, has the amount been equal to that lost

at the surface during the processes which have caused the ups and downs of the land areas? This is a question which does not seem to be susceptible to a definite answer.

If there has not been an increase of heat under the changing areas then with a greater heat under the oceans it would seem that the depth of compensation, if dependent upon heat and pressure only, should be somewhat less under the oceans than under the continents.

After a consideration of the question of the temperature throughout the crust and in the subcrustal material we are still in the dark. All we can do is to speculate and advance hypotheses, and to this there is no limit. Investigators are now advancing the hypothesis that the disintegration of the radioactive elements of the crust can supply all the heat necessary to offset the loss from the sub-aërial and sub-aqueous surfaces.[7] This is an interesting idea and may have much merit.

How the earth became superheated and what keeps up the supply are interesting problems, and their solution would throw much light on the past geological history of the crust of the earth, and its present condition. The heat of the earth is no doubt connected with the way in which the earth was formed. Discussion of the

[7] L. H. Adams, "Temperatures at moderate depths within the earth." *Journal* of the Washington Academy of Sciences, Vol. 14, No. 20; Dec. 4th, 1924.

hypotheses advanced to account for the earth's formation would require more space than available to us, and besides they are set forth in detail in easily available works. For many years the hypothesis of Laplace held sway, but it is now being replaced by hypotheses formulated by T. C. Chamberlin, Harold Jeffreys, and J. H. Jeans.

Whatever the source of internal heat, it is not due to continuous contraction or to pressure on the earth's center by overlying matter. The elastic compression occurs suddenly and then ceases; or at least this is the case with materials under pressures with which we deal in our various human activities. If unconfined, a body subjected to continuous pressure, approaching the elastic limit of the material composing the body, will undergo continuous non-elastic distortion but not additional decrease of volume. I think we must eliminate gravitation as a means of furnishing a continuous supply of heat to the earth's interior.

Some Geological Literature in Which Isostasy is Considered

A number of papers have appeared in which the authors have applied the principle of isostasy to geology. The most notable of these is the one by C. E. Dutton, "On Some of the Greater Prob-

lems of Physical Geology," *Bulletin* of the Washington Philosophical Society, No. 11, 1889. This paper was reprinted in the *Journal* of the Washington Academy of Sciences, September 19, 1925. Other important papers which are worthy of careful study are: G. K. Gilbert, "Interpretation of the Anomalies of Gravity," U. S. Geological Survey, *Professional Paper No. 85, C;* Joseph Barrell, "The Strength of the Earth's Crust," a series of articles appearing in Vols. 22 and 23, *Journal of Geology;* S. G. Burrard, "The Origin of the Himalayan Mountains," Survey of India, *Professional Paper No. 12,* 1912; R. A. Daly, "Oscillations of level in the Belts Peripheral to the Pleistocene Ice-caps," *Bulletin* of the Geological Society of America, Vol. 31, 1920; A. C. Lawson, "Isostasy," *University of California Chronicle,* October, 1924, also "The Geological Implications of the Doctrine of Isostasy," *Bulletin* of the National Research Council, Washington, D. C., Vol. 8, No. 46, 1924; L. H. Adams, "Temperatures at Moderate Depths within the Earth," *Journal* of the Washington Academy of Science Vol. 14, No. 20, 1924; A. Born, "Isostasie und Schweremessung," Julius Springer, Berlin, 1923, (an excellent review of this book by C. R. Longwell, is given in the *Geographic Review,* Jan., 1925); James H. Gardner, "Rock Distortion on Local Structures in the Oil Fields of Okla-

homa," *Bulletin* of the American Association of Petroleum Geologists, Vol. No. 3; Harold Jeffreys, "The earth, its Origin, History and Physical Constitution," University Press, Cambridge, England, 1924; John Joly," Surface History of the Earth," The Clarendon Press, Oxford, England, 1925; C. G. S. Sandberg, "Geodynamische Probleme," Verlag von Gebrüder Borntraeger, Berlin, Germany, 1924; C. K. Leith, "Structural Geology," Henry Holt & Co., New York, 1923; Fridtjof Nansen, "The Strandflat and Isostasy," I Kommission Hos Jacob Dybwad, Christiana, Norway; Willis T. Lee "Building of the Southern Rocky Mountains," *Bulletin* Geological Society of America, 1923; Stephen Taber, "The Active Fault Zones of the Greater Antilles," Report of the International Geologic Congress, 1922; H. F. Reid, "Isostasy and Mountain Ranges," American Philosophical Society, Proc. Vol. 50, 1911; C. E. Van Ostrand, "Some Evidence on the Variation of Temperature with Geologic Structure in California and Wyoming Oil Districts," *Economic Geology,* Vol. 21, No. 2, 1926.

Two books by T. Mellard Reade contain a wealth of valuable material, though the author cannot strictly be classed as an advocate of isostasy. They are: "The Origin of Mountain Ranges," 1886, and the "Evolution of Earth Structure," 1903.

The reader is referred to the short list of papers bearing on isostasy in *Special Publication No. 40,* of the U. S. Coast and Geodetic Survey, and the large bibliography by Adolph Knopf, which appeared in 1924 as a bulletin of the National Research Council, Washington.

CHAPTER IX

PROPOSED THEORY, IN HARMONY WITH ISOSTASY, TO ACCOUNT FOR MAJOR CHANGES IN THE ELEVATION OF THE EARTH'S SURFACE [1]

In geological research we are confronted with the problem of accounting for the uplift and down-warping of the surface of the earth without the permanent addition or subtraction of pressure on the subcrustal base below the affected areas. This accounting is required if the isostatic balance has always existed. The isostatic idea is opposed to the contraction theory as the cause of the major vertical movements of the earth's surface. The "roots of mountains," or Airy, theory of isostasy has so many weak points that it seems to be untenable. It was an attempt to harmonize the isostatic condition of the earth's crust and the contraction theory. The roots theory was a compromise and it served a good

[1] The contents of this chapter, slightly modified, appeared in Gerland's "Beiträge zur Geophysik," Bd. XV, Heft 2, 1926, under the same title.

purpose for a time. It enabled the advocates of contraction to accept the proof of isostasy without having to abandon the contraction theory, which had been so strongly entrenched before the quantitative tests of isostasy were made.

We cannot rest with the theory of isostasy proved. We must search for the cause of uplift and subsidence which occur without a change in the masses of the blocks of the crust below the areas undergoing the changes of elevation. By the process of elimination we seem to be left with the theory that the changes in surface elevations are due to changes in density of the crustal matter below the affected areas. But how can such changes occur and what causes them?

It is well known to the petrologist that substances of the same chemical composition, quantitatively and qualitatively, have different volumetric densities. Probably the most notable example of this is the diamond and graphite. They are each pure carbon, but their densities are respectively 3.1 and 2.5. They no doubt owe their different qualities and appearance to the different pressures, temperatures, and possibly other conditions, under which they were formed. Since the earth's crust has been found to be of the order of 60 miles in thickness, a change in density of less than 2 per cent is necessary to change the elevation of the surface by one mile.

Temperature Variations in Crust

There must be a large change in the temperature of the crustal material under an area which has been subjected to great amounts of erosion or sedimentation. As material is eroded from the surface of one area and is deposited in another, the former is subjected to uplift and the latter to subsidence in order that the isostatic balance may be restored. The uprising crust is forced into colder spaces while the crustal matter which sinks under the sediments is forced into spaces which normally have higher temperatures.

Suppose the temperature gradient found for the first mile of the earth obtains throughout the 60 miles of the crust. This gradient varies greatly from place to place near the surface, but the average is about 50 degrees centigrade per mile. If the erosion from a certain area has been 5 miles, and this is not an excessive amount, the difference in the temperature of the space formerly occupied by the affected matter and of the space it now occupies is of the order of magnitude of 250° C. The new location is lower in temperature than the former one by that amount. Again suppose there had been a sinking of 5 miles under sediment in some other area. In this case the crustal matter will have moved to spaces whose normal temperatures are 250° C. hotter

than the locations formerly occupied. This applies not only to the material which had been at the surface but to the material throughout the whole length of the block of the crust that is involved in the movement downward. Of course we have no direct evidence that the temperature gradient is the same throughout the crust, but with so little evidence to work with we must make some assumptions in order that any progress may be made in attacking the problem of unravelling geological history. It goes without saying that any assumptions made should be reasonable ones.

Let us assume that the geoisotherms, or surfaces of equal temperature (see Fig. 33), are parallel to the generalized surfaces of the continents for a depth of about ten miles, and that for the remainder of the crust these surfaces are parallel to the sea-level surface. This is a pure assumption for it is impossible to get any evidence as to just how the geoisotherms are spaced with depth under continents and oceans. But to be able to speculate on what happens when the crust of the earth is depressed or elevated some assumptions must be made as to the temperature gradients.

With a change in temperature of 250° C. in a 60-mile column of rock having a thermal coefficient of linear expansion of 0.000012, which is that of marble and probably about that of the

igneous rocks composing the earth's crust, the change in length due to the cubical expansion concentrated in one direction would be about 2850 feet. This is much smaller than the average elevation of mountain systems. Therefore either the coefficient of expansion of material under

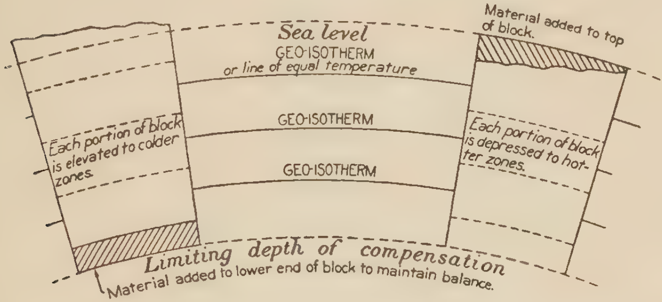


FIG. 33.—Erosion and sedimentation cause loading and unloading of portions of the earth's crust. Crustal matter is forced into hotter regions by the weight of the sediments and forced up into colder regions as the isostatic adjustment restores the equilibrium of the crust below areas of erosion. The earth's materials change their temperatures slowly. The geoisotherms, or surfaces of equal temperature, are depressed under the sedimentary area and raised up beneath erosion areas. As the geoisotherms approach their normal depths crustal material will be increased or decreased in temperature. Ordinary thermal changes in density will occur but it seems probable that physical or chemical actions take place which cause changes in elevation above the affected crust.

the very great pressures of miles of rock is far greater than at the surface, which does not seem probable, or there has been contraction and expansion of rock due to some process other than thermal contraction or expansion as we know it. We seem to be left with the idea that there has occurred an expansion or contraction in addi-

tion to the changes of volume due to ordinary thermal expansion. What the process is we do not know, but it is probably associated with the changes of temperature and pressure. Perhaps physical or chemical reactions of some kind, or a combination of the two, cause this additional change in density and volume. If these changes in volume do not occur, then the isostatic principle is false. But the principle of isostasy is supported by what is generally recognized as overwhelming evidence.

In the absence of anything better let us assume the theory that the major changes in the elevation of the earth's surface are due to changes in the density and volume of the crustal material below these areas which undergo the great changes in elevation, and see what should be the sequence of events. It seems necessary to assume that changes in the positions of the geoisotherms, in the moving matter as it goes to normally hotter or colder spaces, is slower than the vertical rates of erosion and sedimentation.

Beginning of Cycle of Mountain Formation

The theory about to be set forth leads to a cyclic process whereby a given area may be alternately an area of deposition and an area of erosion. Obviously the recurrence of this cycle

cannot be continued backward into an indefinitely remote past, and some explanation must be given as to how the cycle started. Fortunately we have a clue to this process in the discovery of Henry S. Washington that there are what he terms comagmatic regions. He has found that there is a rather definite relation between the *norm* derived from the atomic weights of the chemical elements composing magmatic material now exposed at the surface and the elevation of the places where the specimens of magmatic rock have been found. This would lead us to the conclusion that before the beginning of the sedimentary age the earth's surface was irregular, with depressed and elevated regions. This irregular surface will be taken as the starting point of our speculations and no attempt will be made to explain how the irregularities came about.

When the water began to fall, it collected in the low ground forming the oceans and inland seas. The bottoms of the bodies of water were depressed by the weight of water such an amount as was necessary to balance in weight the crustal prisms under the water and the land areas. Since the water area of the earth is much greater than the land area, the subcrustal matter displaced was less than half the mass of water. If the two areas had been exactly the same and if the water areas had been covered by a uniform depth of

water, then the displaced subcrustal matter would have been just one-half the mass of the water. This depression of the low areas under the water caused an elevation of the high or land areas to restore the equilibrium.

The collection of the waters into the basins caused very little erosion but, with the continuous process of evaporation, precipitation and runoff which must have occurred during the sedimentary age, great beds of deposits were laid down in the ocean and sea areas. The crust below the sediments was depressed an amount equivalent to the thickness of the material in the lower part of the crust equal in mass to the difference between the mass of sediment and the mass of the water displaced. If the depth of the displaced water was 5000 feet, then the increased load represented by the sediments was equivalent to 3150 feet of material of density 2.7. Supposing the density of the material at the bottom of the crust to be 3.0, the layer of this matter that would exactly balance the added weight of the sediments would be 2835 feet. It may be assumed that the crust sank beneath this body of sediments leaving still some water above them. The continued process of sedimentation would go on until the surface of the sediments was at sea level and the total thickness would then be 11,550 feet. At that time there could have been no independent sinking of the crust beneath the sediments except the very slight amount due to the elastic

compression of the crustal material subjected to the weight of the sediments. This was very small in amount.

As the sediments filled up the water spaces near the shores the sediments were carried farther and farther to sea. The geoisotherms were depressed under the sediments but they did not rise to their normal positions for some time after the sediments had been laid down. Later they rose to their normal positions heating up the crustal material throughout the column, thus causing the expansion which furnished the first plateau or the first mountain system composed of sedimentary material. It seems probable that some such process as that outlined above must have started the cycle of uplift and sinking that has been going on during the sedimentary age.

That there has been adequate sedimentation during this time is indicated by the rate of erosion that we now have in the United States. According to the reports of the U. S. Geological Survey about one foot, on the average is eroded from the area of the United States in nine thousand years. At that rate a mile of material could be eroded from our area in about 45,000,000 years. There have been various estimates of the time which has elapsed since the beginning of the sedimentary age but the one that seems to have gained most favor is a billion and a half years. In such a time as that, erosion would have been carried on to the extent of some 30 miles.

Of course the configuration of the area of the United States has changed from time to time and no one area could have been subjected to erosion continuously. (See p. 187.)

There has been tremendous rainfall during the sedimentary age. The average for the land area of the world is now about 30 inches per year. This is equivalent to a mile of rain in approximately 2000 years and, if the rate of rainfall was the same throughout the sedimentary age, something like ¾ million miles has fallen. We have, in the rainfall and the rate of erosion, evidence of the tremendous shift of material over the earth's surface which seems to have been the cause of the great changes in elevation.

With the initial irregular earth surface and the early sedimentation made possible by the primordial irregularities of the surface, we have the beginning of the processes which led to the major changes in elevation that have since been going on. The process once started would tend to perpetuate itself as is shown in the discussion which follows.

Retardation of Base Leveling by Isostatic Adjustment

As material is eroded from a high area an equal mass of subcrustal matter enters the crustal space to restore the balance. The amount of up-

ward movement will not be equal to the thickness of the eroded matter. The average density of surface rock is about 2.7. It is not known what is the density of subcrustal rock but it is probably at least 10 per cent greater than that of the surface rock. Let us assume this difference. Then if 1000 feet of rock are eroded from an area, the layer of subcrustal rock which is equal in mass is only 900 feet in thickness. The surface then, would be lowered only 100 feet as a result of the erosion of the 1000 feet. According to this reasoning it is necessary to erode 10 miles of material from the surface of an area one mile in average height in order to bring it to sea-level. If the difference in the densities of surface and subcrustal rock is greater or less than 10 per cent then the ratio of the elevation and the amount of erosion needed to base-level the area will, of course, have a proportional change.

It is well known that the volumes of sedimentary materials derived from previously elevated areas are far greater than any mountain mass which could have existed at one time. Some of the ancient mountain systems have been given elevations far in excess of any elevations we have today. These elevations were estimated from the amount of sedimentary material which must have been derived from them. With the theory that the crust under an area undergoing erosion is continually rising up, as materials are carried

away, it is not necessary to postulate such great and unreasonable heights for the ancient mountains which have since disappeared.

Even though the uplift, as erosion is progressing, may be faster than the depression of the geoisotherms, due to loss of heat to the sides and at the surface of the upmoving crustal matter, there will be time enough for some change in temperature before the area has been base-leveled. It seems reasonable to assume that the affected matter will not acquire the temperatures that are normal to its new positions for a considerable time after the area has been base-leveled. It is probable that the surface remains at a low and approximately fixed elevation for some time after the base-leveling before the effect of the change in the temperature of the crustal material makes itself felt. The change in volume from thermal contraction will take place as the column loses its heat with its upward movement, but subsequent behavior of the surface leads to the idea that the increase in density and decrease in volume from the other causes begin only after the geoisotherms have moved to or near their normal depths.

Beginning of Sedimentation after Area has been Base-leveled

When the down warping of the surface has

progressed to a certain amount a trough is created. The area will sink below the elevation of the surrounding regions and become the region into which rivers will deposit their sedimentary loads. Such an area is usually spoken of as a geosyncline. It seems that the shrinking of the crustal material continues for a long time after sedimentation of the area begins. This must be true, for there is a sinking of the crust beneath active sedimentation which is independent of the sinking that is due to the weight of the sediment.

Sediment Largely Deposited in Shoal Water

The sediments are a load on the crust and when they have accumulated to a considerable degree the crust below is pushed down under their weight. If this were not so, then there would be a departure from equilibrium. The geodetic data show that sedimentary areas are in isostatic equilibrium. Therefore the sediments are balanced by a subcrustal movement below the area undergoing sedimentation. But the density of the sediments in place is not over 2.4 or 2.5 until after they have been consolidated. The density of the material at the bottom of the crust must be 3.0 or close to that. In any event it must be from 10 to 20 per cent greater than the density

of the newly placed sediment. We are of course speaking here of the volumetric density of the sediments rather than their specific gravity. With this large difference in density a layer of sediments 1000 feet in thickness would require a layer of matter at the bottom of the crust of from 800 to 900 feet in thickness to move away to restore the equilibrium. This would leave the surface from 100 to 200 feet higher than it was before the beginning of the sedimentation of the area. If the sinking of an area were due to the weight of sediment alone, the application of only a few thousand feet of material would raise the surface so high that the rivers would flow off to other places. It would be impossible to have many thousands of feet of sediment deposited over an area, all in shoal water, when the only force causing the downward movement is the weight of the sediment. There is another cause of the sinking independent of the weight of the sediment and that is the contraction of the crustal material beneath the sedimentary area. That contraction seems to result from processes set up by the change in temperature of the crustal matter as a result of the upward movement of that matter when the surface above it was undergoing erosion.

Beds of sediment 20,000 feet in thickness, and even more, have been laid down in shallow water along the margins of oceans and of inland seas,

so there must have been contraction going on during the entire time of sedimentation. When this contraction ceased there was a cessation of sedimentation in the area, although the sediment may then have been carried farther out to sea, thus broadening the sedimentary zone.

It is evident from the preceding reasoning that the only areas close to a continent which can undergo great sedimentation are those which have been areas of heavy erosion. Of course deep areas of the oceans beyond the continental shelves can have thick beds of sediment laid down on them without an independent sinking of the area, but the sediment would give evidence of having been deposited over a wide range of depths of water. Existing mountain systems contain evidence that the sedimentary rocks in them were deposited in shallow water.

It is improbable that the crustal material below an area undergoing sedimentation could be decreasing in temperature. The crust is going down under the weight of the sediment. The crustal matter is moving to spaces of greater normal temperatures and should be getting hotter rather than colder. We are justified in holding that the crust has assumed the temperatures normal to the positions occupied by its separate units at the time, or not long after, sedimentation began. Also we seem to be drawing a reasonable conclusion in postulating that the processes that

contract the crustal matter as a result of the cooling following erosion act for a long time after the area begins to sink. The chemical or physical processes which cause the contraction must work slowly. The length of time is measured by the period during which the sediment is laid down over the affected portion of the crust.

Theoretically the thermal gradient for the first mile under an area undergoing rapid sedimentation should be less than that under an area that is undergoing erosion or under a stable area. But it is practically certain that the temperature increases with depth even in the sedimentary layers. This may be due to an increase in the whole column including the sediment or to the cooling of the crustal matter just under the sediment, the heat being conducted to the sedimentary layer.

Uplift of Sedimentary Area to Form Mountains

The uplift of an area seems to be due to just the reverse of the processes which have been under discussion. We must have an increase in volume and decrease in density in order that the isostatic equilibrium may be maintained. If a mountain system were an extra load on the subcrustal base, the geodetic data used to test isostasy would surely indicate the lack of balance.

While the mountain systems of the world have not all been tested for isostasy, yet those which have give results most satisfactory to the isostasist. It is not unreasonable to conclude that the other mountains if tested, would show equally satisfactory results.

All existing mountain systems give evidence that the areas they occupy were formerly subjected to heavy sedimentation. This leads us to the opinion that there is some fundamental and necessary relation between sedimentation and uplift. A search for this relation leads us to the conclusion that the pushing down of the crustal matter to hotter regions, by the weight of the sediments, is the cause of the subsequent uplift. It is not that part of the sinking which results from the contraction, previously discussed, that afterward causes the expansion, but that part which is due to the weight of the sediments.

If the thickness of a bed of sediments is 30,000 feet, each element of the crust below has been forced down approximately a like amount. The amount of sinking would be somewhat different at different depths. At the surface the sinking is exactly the same as the thickness of the sediments, that is, within a few hundred feet. At the bottom of the crust the downward movement is equal to the thickness of the sediments multiplied by the ratio of the density of the sediments to the density of the crustal matter at the lower

part of the crust, which was forced into sub-crustal space to restore the equilibrium. Intermediate elements of the crustal matter would have vertical movements somewhere between that at the surface and that at the lower part of the crust. The average downward movement of the crust under 30,000 feet of sediments therefore would be of the order of magnitude of 27,500 feet, or about 5½ miles.

If the temperature gradient at the surface obtains through the 60 mile crust, the crust would, on an average, be forced into a space about 275° C. hotter than it previously occupied. The effect of the subsequent rise in temperature would be an elevation of the earth's surface by ordinary thermal expansion, but this expansion would be less than 3,000 feet. There would be an additional expansion due to physical or chemical processes which would further increase the volume and decrease the density of the crustal matter. (See Fig. 34.)

There may be some increase in the temperature of the sinking matter as the down movement takes place, but it is not possible that the geoisotherms could maintain their normal positions, for, if they do, the processes which are at work to cause the sinking of the area independent of the usual thermal contraction would be offset and the contraction would cease.

This could not be the case for there is down-

ward movement during the whole period of sedimentation. The contraction which started while the area was still an erosion area began at such time as the cooling had progressed to a certain point. The contraction processes apparently could not begin until there had been a consider-

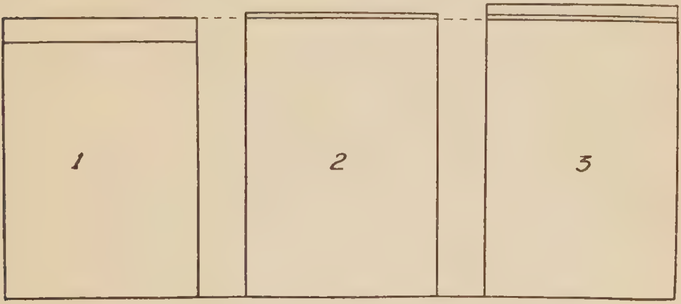


FIG. 34.—A prism of the earth's crust, subjected to sedimentation, is pushed down into hotter regions. When the crust takes on the new temperature, its surface will be raised by normal thermal expansion. Other causes expand the crust to give additional elevations of the surface. In prism 1, assume that there have been added 30,000 feet of sediments. The upper portion of prism 2 shows expansion by normal thermal action. The upper part of prism 3 shows the expansion by other causes.

able change in temperature. The continued loss of heat to depress the geoisotherms to their normal positions would of course increase the activities of those processes. It seems necessary to assume that the contraction continues for a long time after the thermal surfaces have reached their normal positions.

The cessation of the sedimentation of an area may be due to one of the following two causes: 1st, the completion of the denudation of the area

from which the sedimentary materials were derived; 2nd, the cessation of the processes that were causing that part of the sinking which is independent of the sinking caused by the weight of the sediments.

It is probable that there is a lapse of a considerable period of time between the end of the sedimentation of an area and the time that the uplift to a mountain system or a plateau begins. The contracting must have continued throughout the period of sedimentation and at the end of the period the geoisotherms must have been below their normal positions. Otherwise the condition that caused the contraction would have been offset.

As the geoisotherms rise the causes of independent expansion also become active, and an augmented uplift of the surface occurs. This activity increases in rate until the geoisotherms reach their normal positions. Coincident with the uplift, erosion begins. It is slow at first but increases in rapidity with the increase in the elevation of the surface. The processes of expansion continue to operate until the mountain system or plateau has reached maturity. The average elevation of the surface would not increase after the expansion had ceased, but the elements of the crustal matter below would be raised in position as the isostatic adjustment offsets the removal of surface materials by denudation.

The Causes of Surface Changes

A careful weighing of all the data and other evidence available leads to the conclusion that the primary causes of at least the major changes of the earth's surface are evaporation, precipitation, erosion, and sedimentation. Resultant causes are the maintainance of the isostatic balance by the horizontal movement of subcrustal material, and the expansion and contraction of crustal material under areas of sedimentation and erosion, respectively, due to changes of temperature of the crustal matter.

Summary of Chapter IX

The process just explained may be stated in summary and schematic fashion in connection with Figs. 35 to 38, which illustrate its various stages.

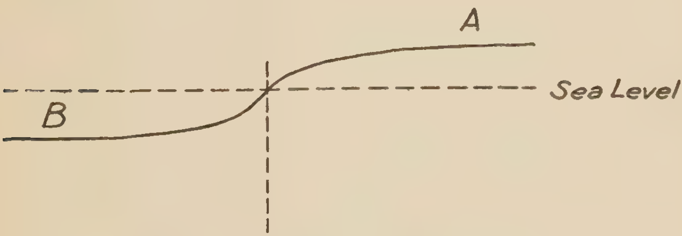


Fig. 35.—Beginning of sedimentary age.

Before sedimentation began the earth's surface was irregular with broad basins and wide

uplands (see Fig. 35). When erosion began *A* rose and *B* sank to restore the isostatic equilibrium. There was no rising or sinking of the surface independent of the isostatic adjustment.

In Fig. 36 is shown one stage of a later cycle.

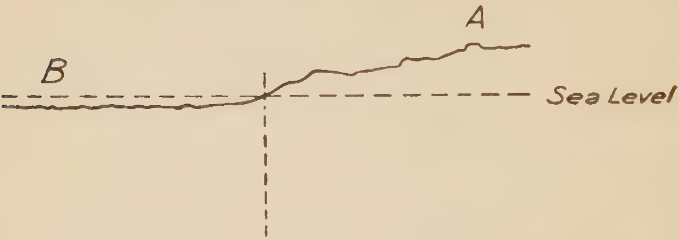


FIG. 36.—First stage of a cycle of erosion and sedimentation.

A is an area of erosion which is rising owing to relief of load but not as fast as the material is eroded. *B* is an area of deposition and sinks under the load of sediment. There is also a continuation of the independent contraction under

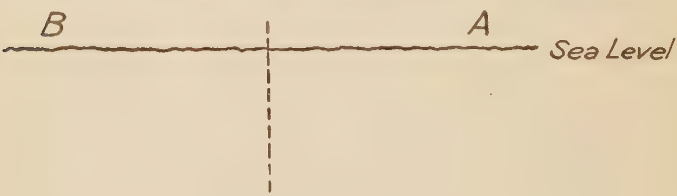


FIG. 37.—Second stage.

B, started by previous erosion, and the subsequent lowering of geoisotherms which had been displaced upward.

A second stage of the cycle is shown in Fig. 37.

A has been base-leveled to *B* and there is comparative quiescence as independent contraction of the *B* prism slows down and ceases. The geoisotherms are now depressed in the *B* prism below their normal position with respect to the surface, and in the *A* prism they are elevated above their normal position.

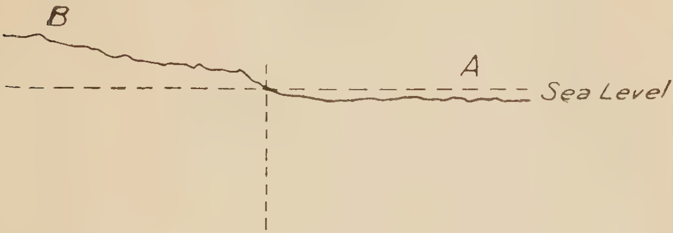


FIG. 38.—Third stage.

A third stage of the cycle is illustrated in Fig. 38. As the geoisotherms tend to return to normal, independent expansion begins in the *B* prism and independent contraction in the *A* prism. This is the dominant effect until there is considerable difference in elevation between *A* and *B*, that is, until *A* and *B* have reversed their situations as compared with the first stage (Fig. 36), and erosion of *B* becomes dominant over independent expansion. This stage completes one half of the entire cycle.

The second half of the cycle is like the first except for the interchange of *A* and *B*. On the completion of the full cycle, *A* is again an area

of erosion and *B* of deposition as in the first stage (Fig. 36).

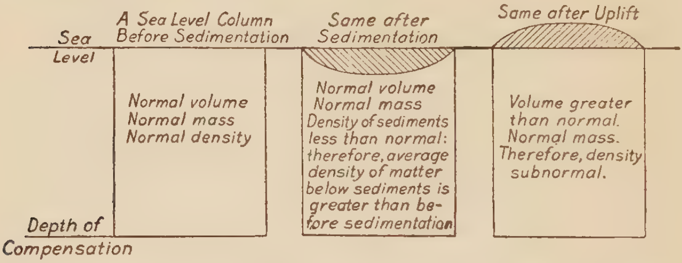


FIG. 39.—Mountain systems occupy areas which were, at former times, at or below sea level. There are other areas now at a low elevation, which were formerly occupied by mountains. It seems probable that changes in density of crustal material below the affected areas must have occurred to change the surface elevations.

It should be stated that the above theory is based on a number of assumptions. The system worked out may seem to be too simple, but its strong point is that it apparently does no violence to the established principle of isostasy.

AUTHOR INDEX

SUBJECT INDEX

73-1